



Fukushima: Status for en igangværende ulykke

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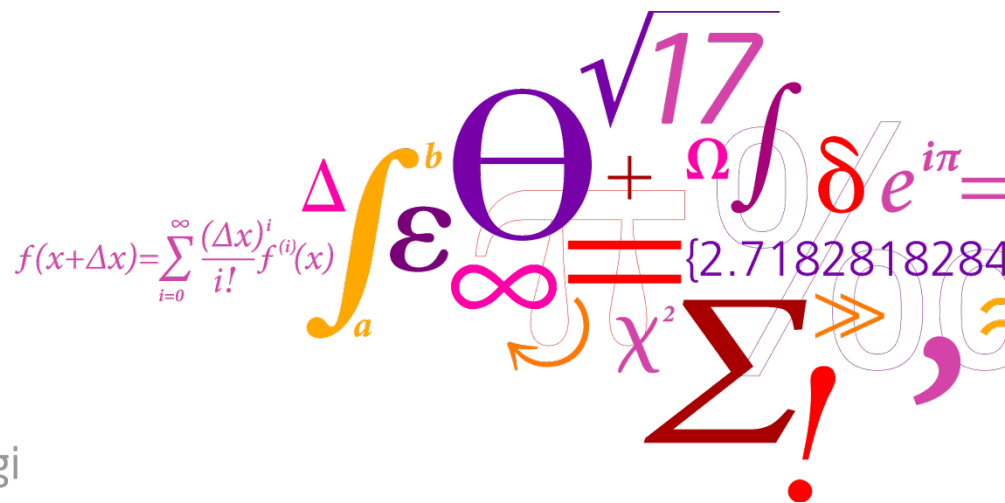
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Fukushima: Status for en igangværende ulykke

Bent Lauritzen og Erik Nonbøl

Risø DTU

20. september 2011



Risø DTU

Nationallaboratoriet for Bæredygtig Energi

Outline

- Kernekraft – hvorfor og hvordan
- Fukushima ulykkens hændelsesforløb
- Status pr. 7. september 2011
- Kernekraft efter Fukushima

DTU og Risø DTU

Danmarks Tekniske Universitet (DTU)

- 7000 studerende, 4200 ansatte, omsætning 3,2 mia. kr.

Risø DTU er nationallaboratorium for bæredygtig energi

- 700 ansatte, budget ca. 550 mio. kr.



Hvorfor kernekraft?



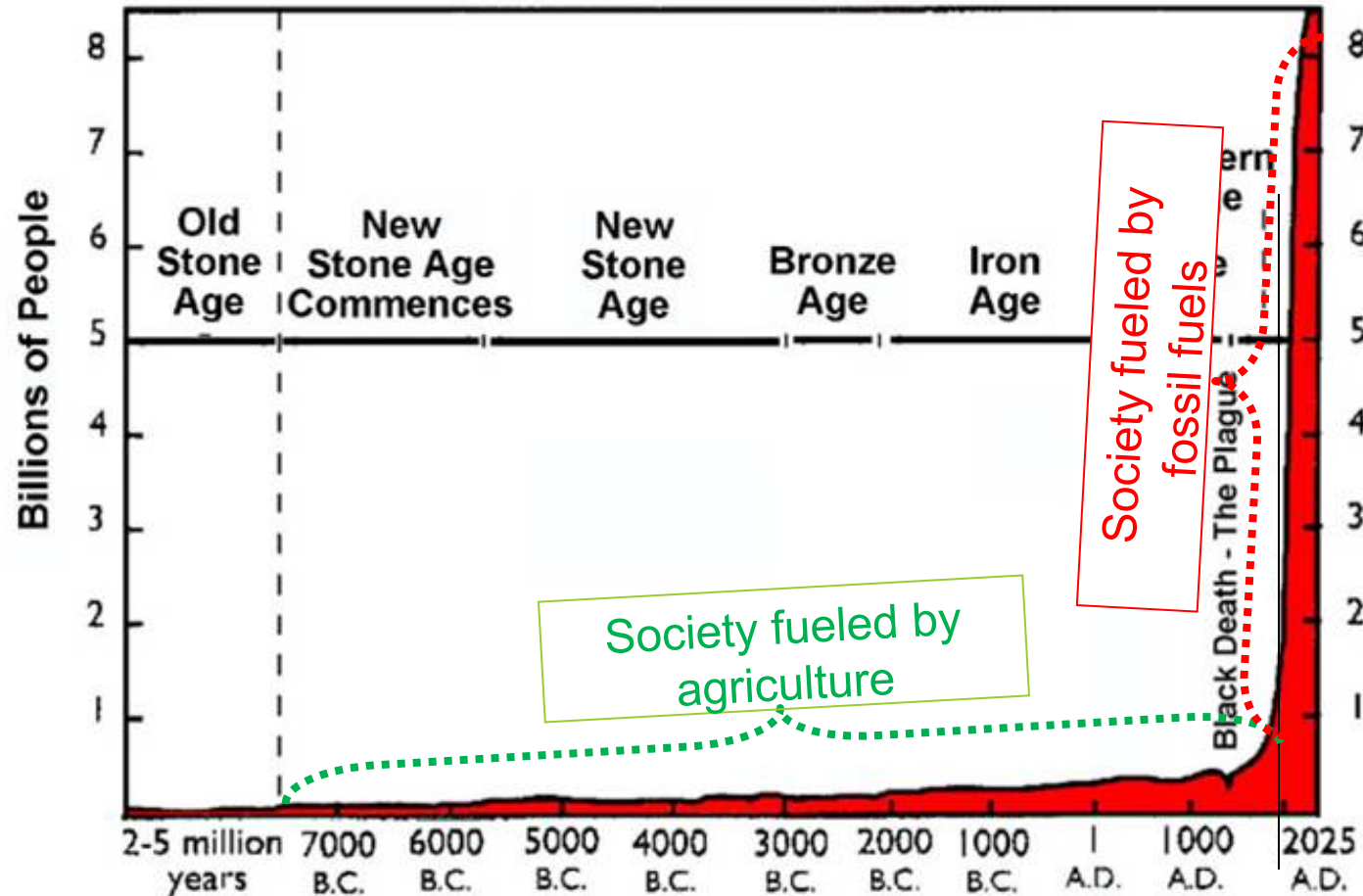
Hvorfor kernekraft?



- **Vi mangler energi**
- **Vi tager ikke hensyn til klima og miljø**

1. Overbefolkning?

History of humans in numbers and technology



From "World Population: Toward the Next Century," copyright 1994 by the Population Reference Bureau

Verden i dag - energiforbrug



Megabyer 2050



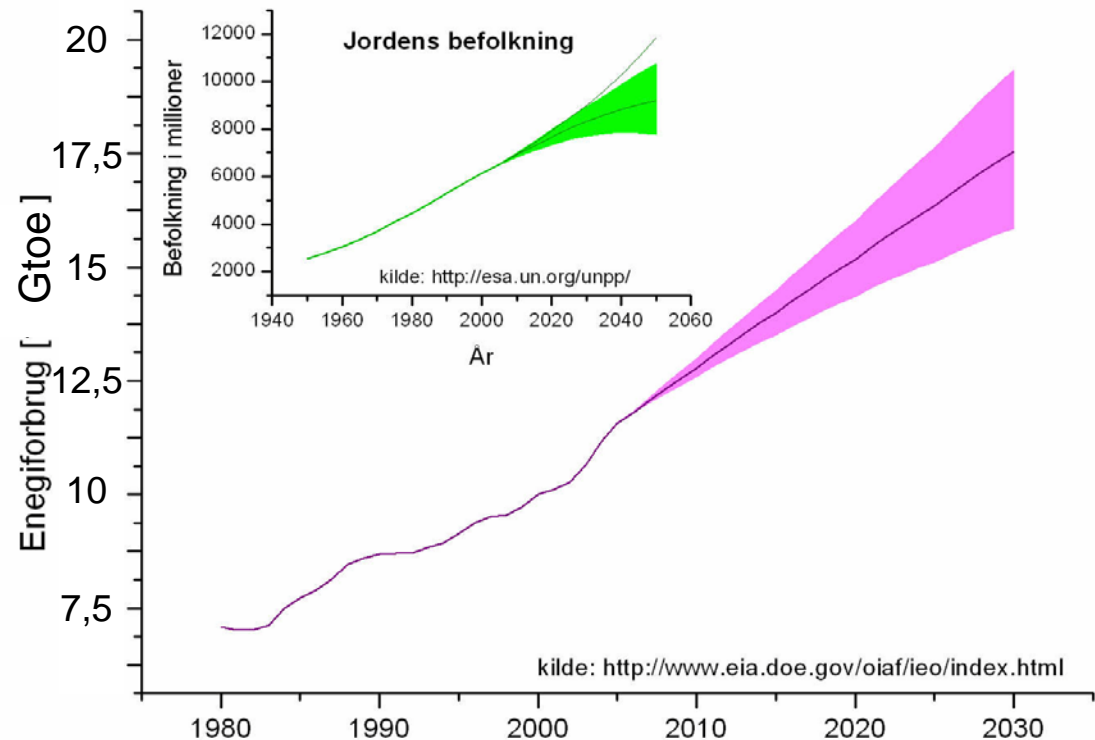
Kilde: Electric Power Research Institute

UNF Odense 22. september 2011

Global Energimangel?

- Vi er ca. 7 milliarder mennesker på Jorden
- Vi bruger energi svarende til ca. 12 mia. ton olie om året.
- Forbruget er voksende fordi:
 - Indbyggerantallet vokser
 - Forbruget pr. person vokser.

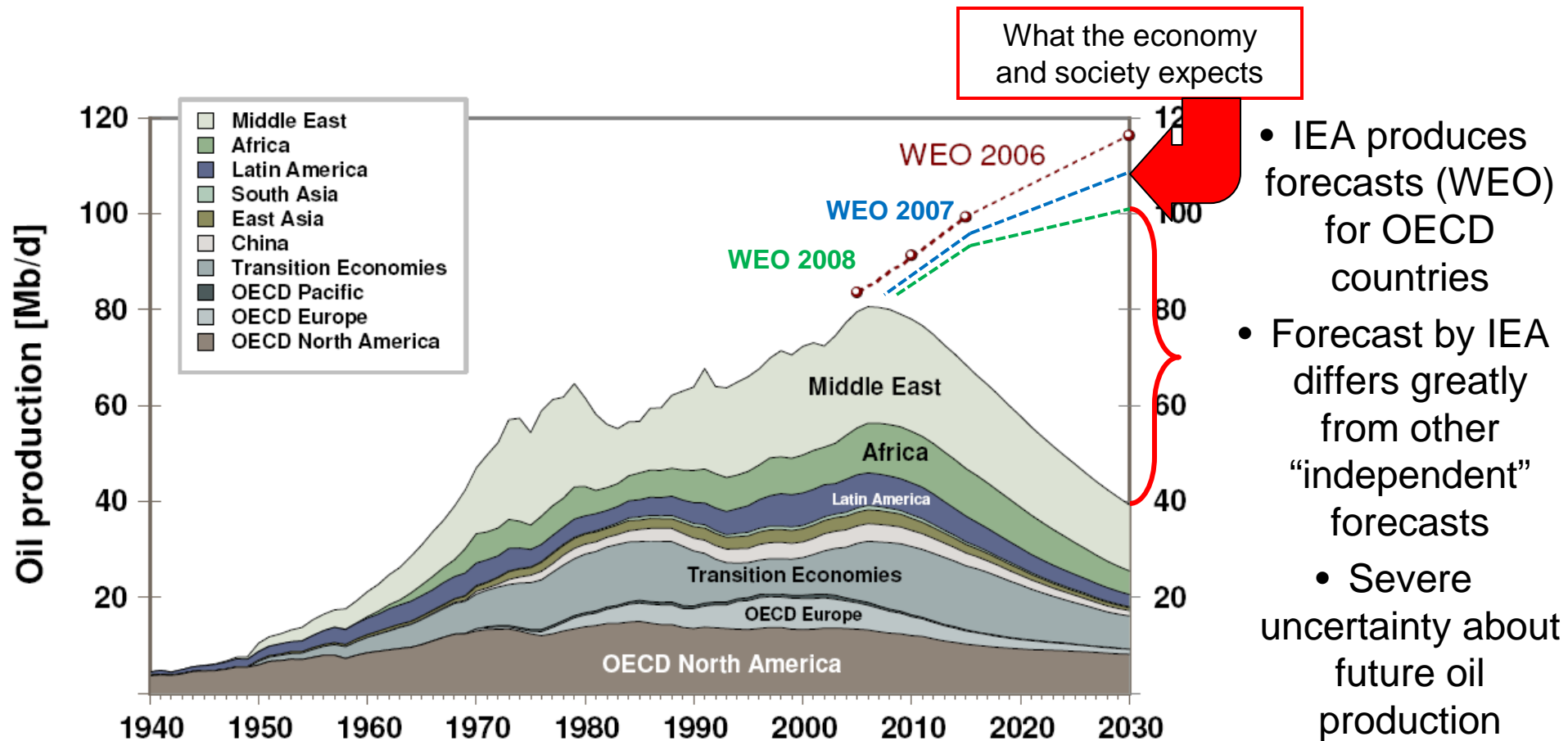
Verdens energiforbrug



Global Energimangel?

- Danmark bruger 829×10^{15} joule / år = 26 GW
- **En Dansker** bruger **5.3 kW**
- **En Kineser** bruger **0.5 kW**
- Kineserne vil indhente os, så
de åbner et nyt kraftværk **hver 2. uge!**
de åbner et nyt kraftværk **hver uge!**

Different forecasts of future oil production: “mind the gap”

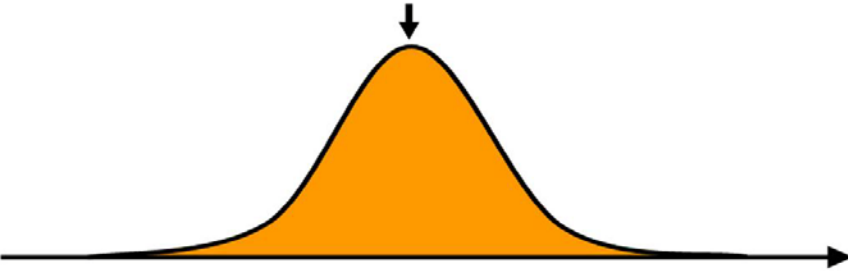


From: Energy Watch Groupe (2008;12), *Crude Oil – The Supply Outlook*

http://www.energywatchgroup.org/fileadmin/global/pdf/2008-02_EWG_Oil_Report_updated.pdf

Wake up!!!

We are here

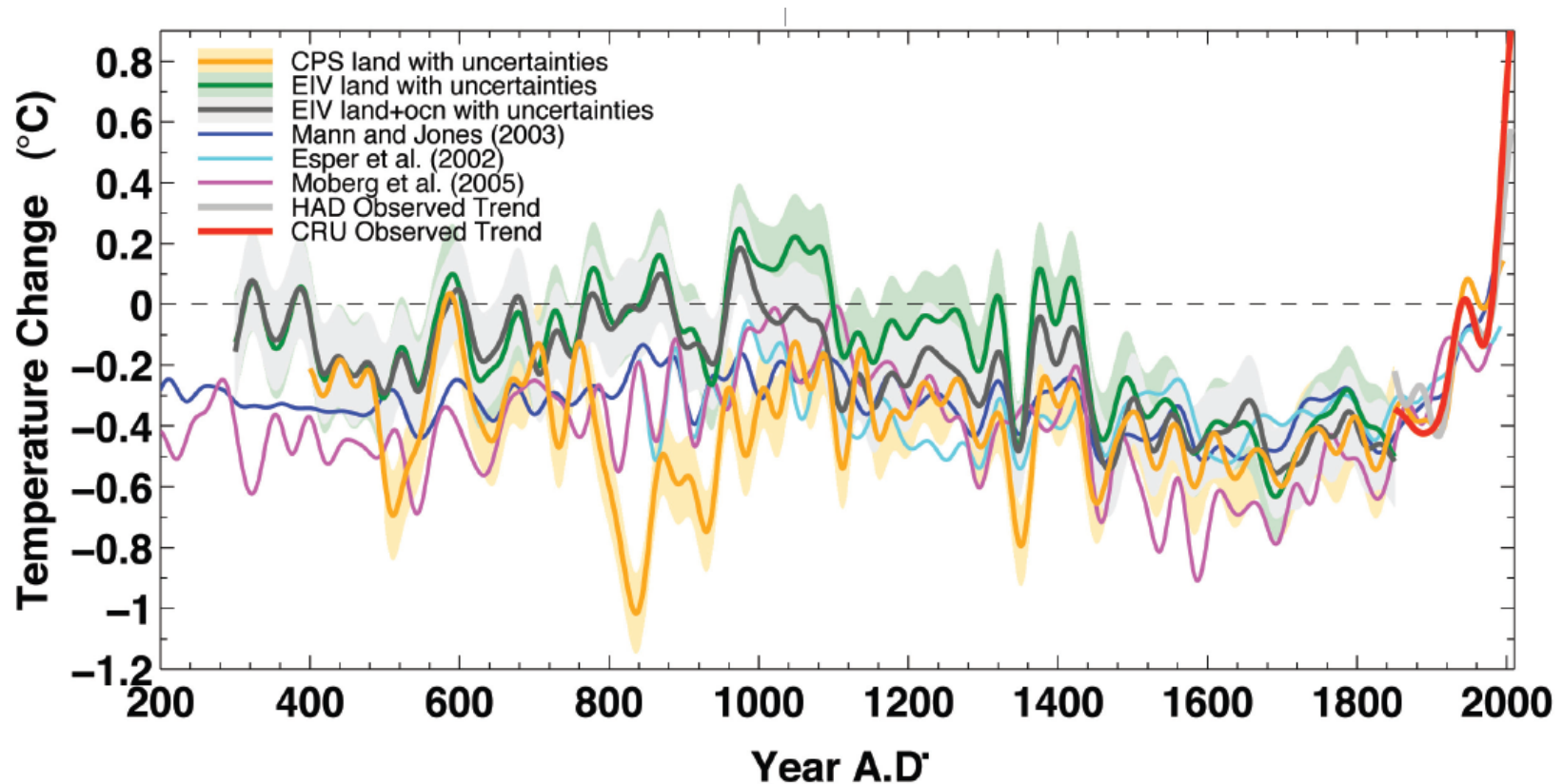


Peak Oil

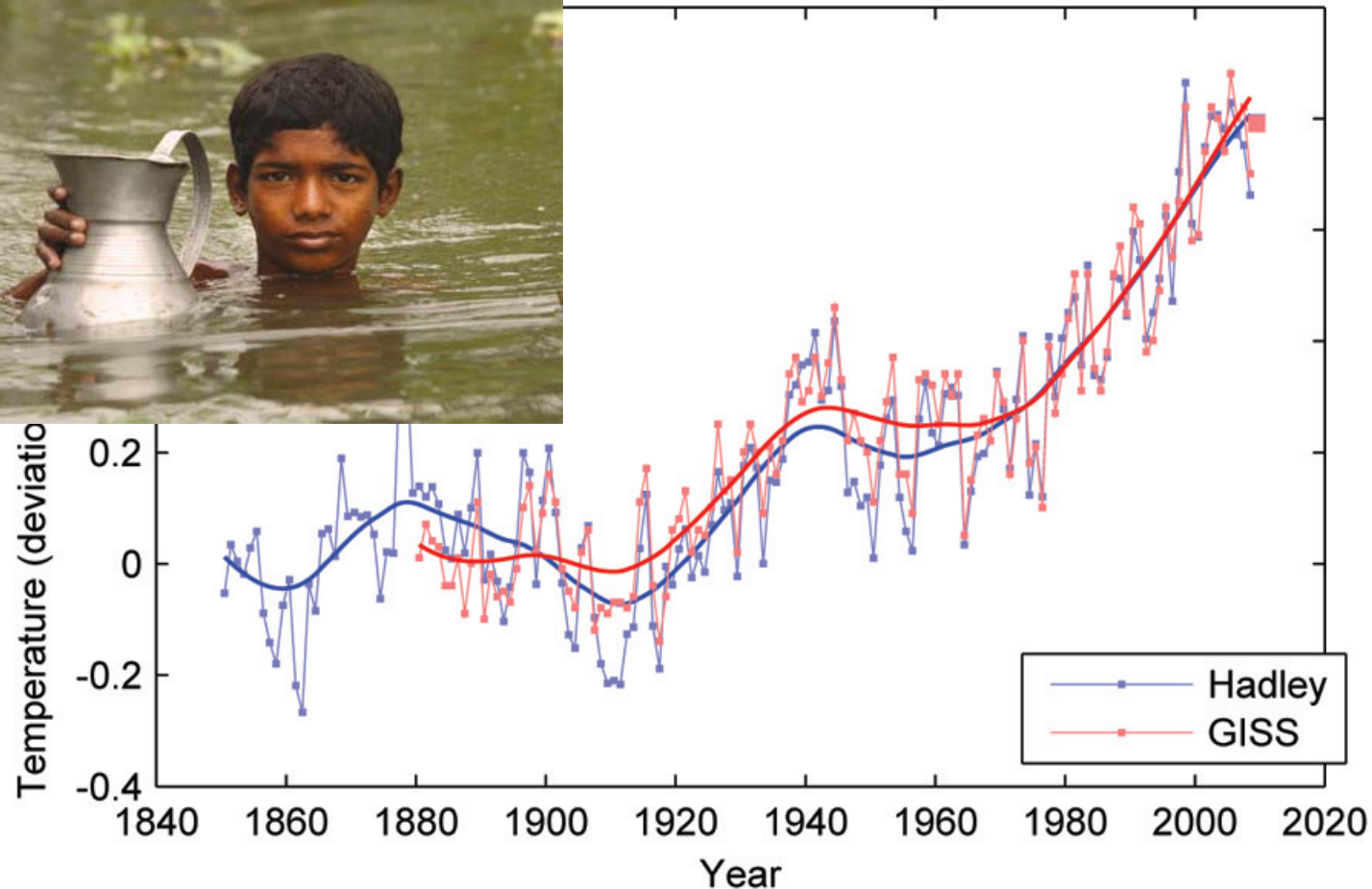


2. Miljø og klima:

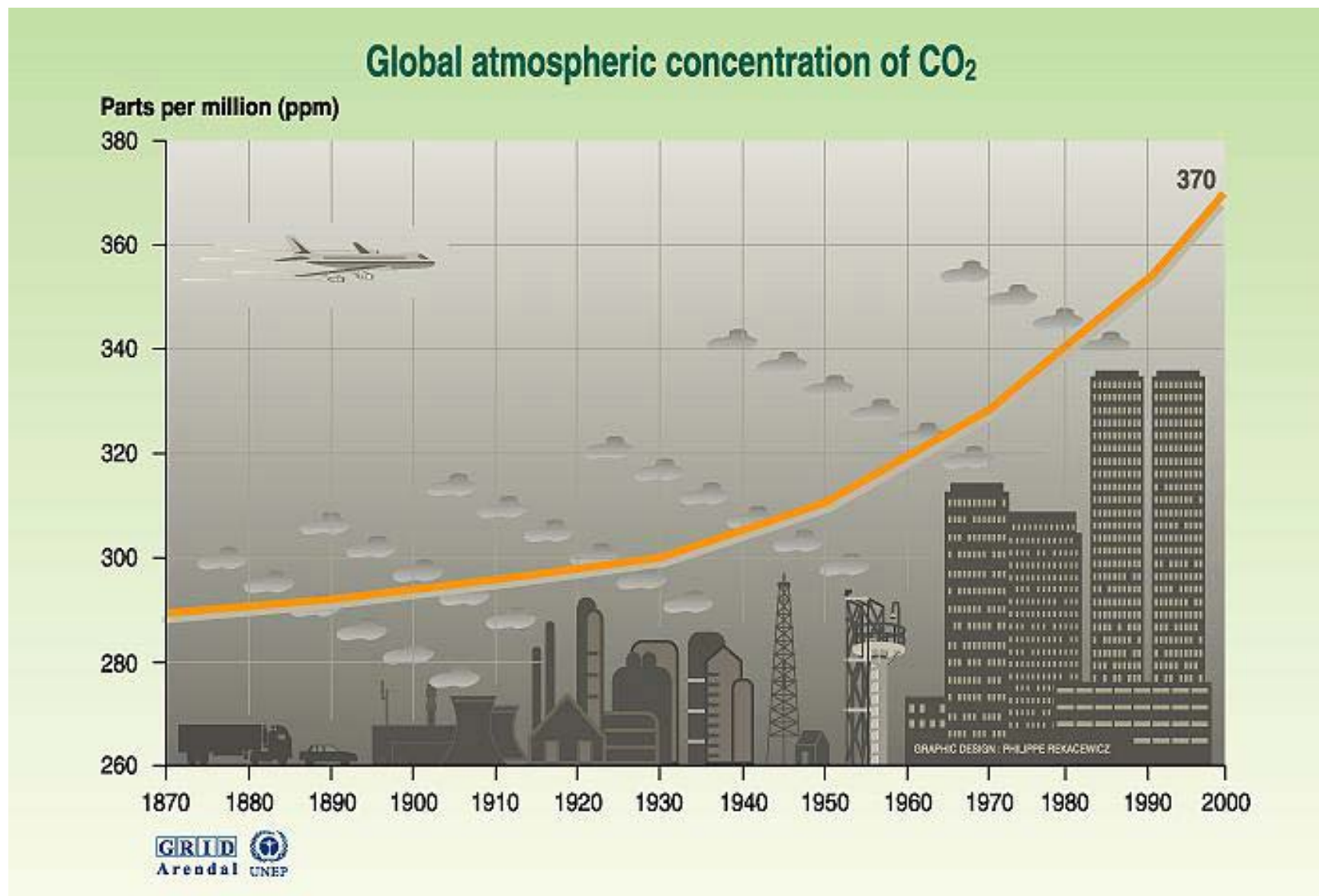
The “hockey stick” - Northern hemisphere temperature



Global average temperature 1850-2009 relative to the baseline period 1880-1920

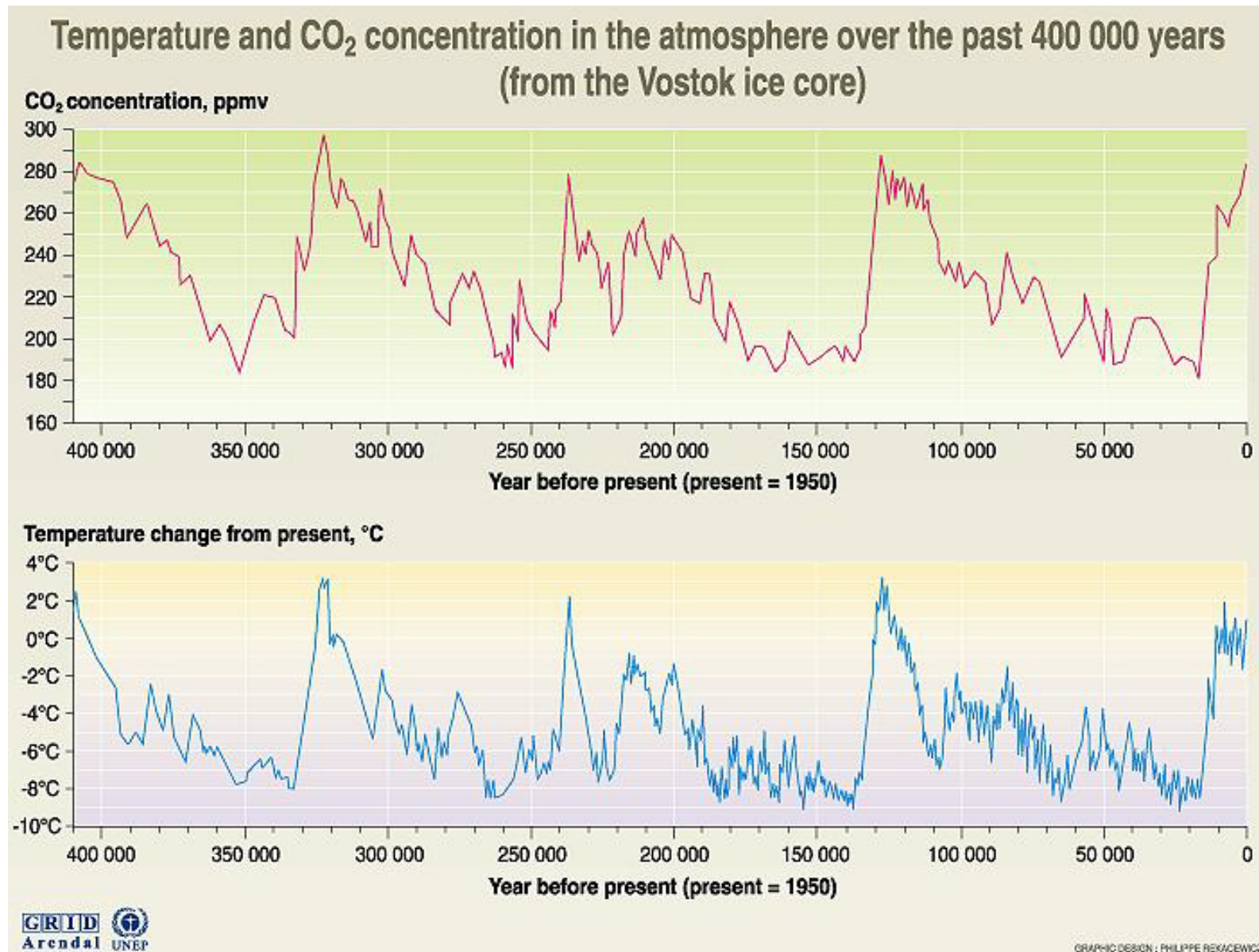


Atmosfærens CO₂-koncentration



Sources: TP Whorf Scripps, Mauna Loa Observatory, Hawaii, institution of oceanography (SIO), university of California La Jolla, California, United States, 1999

Atmosfærens CO₂-koncentration



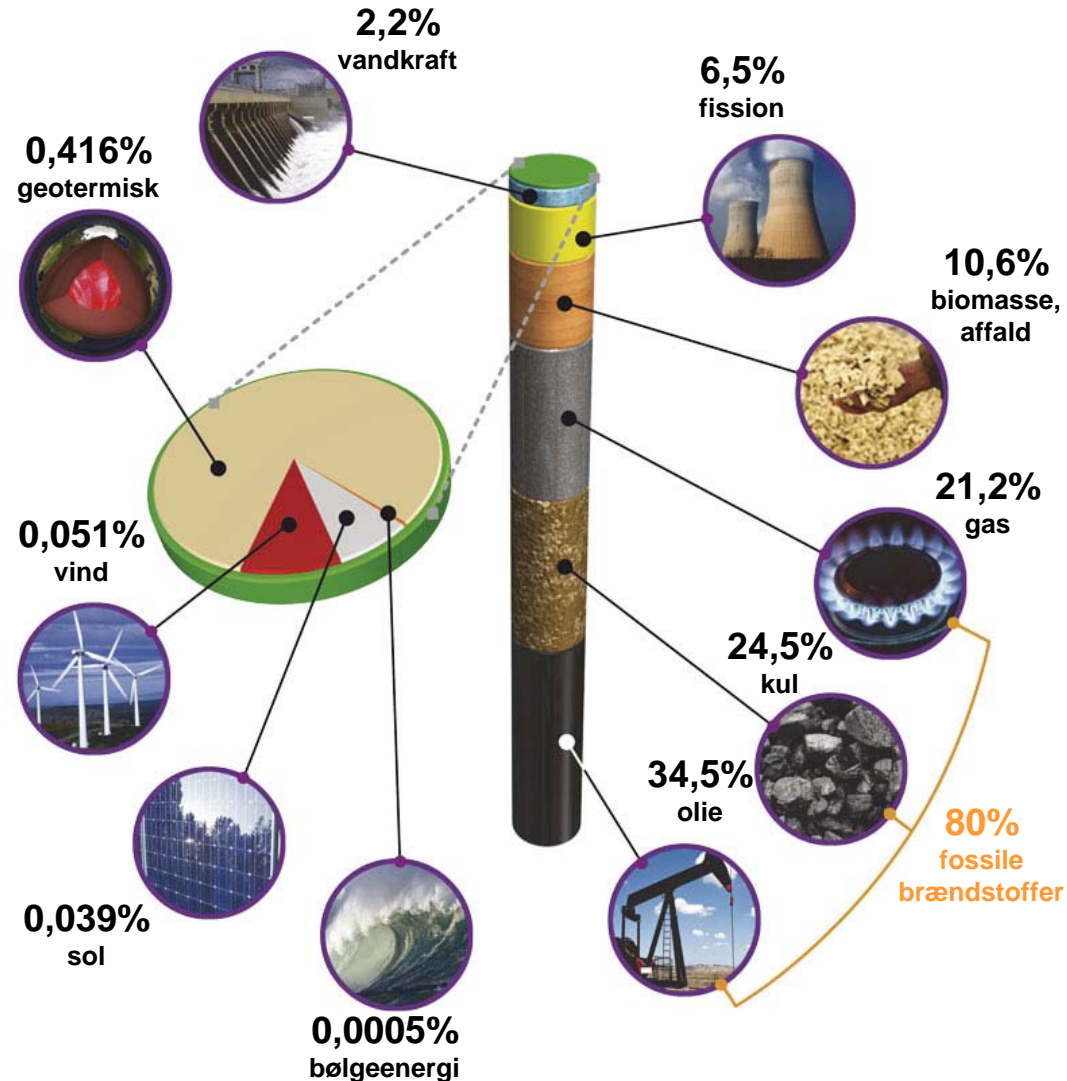
Source: J.R. Petit, J. Jouzel, et al. Climate and atmospheric history of the past 420 000 years from the Vostok ice core in Antarctica, Nature 399 (3June), pp 429-436, 1999.

The final proof:



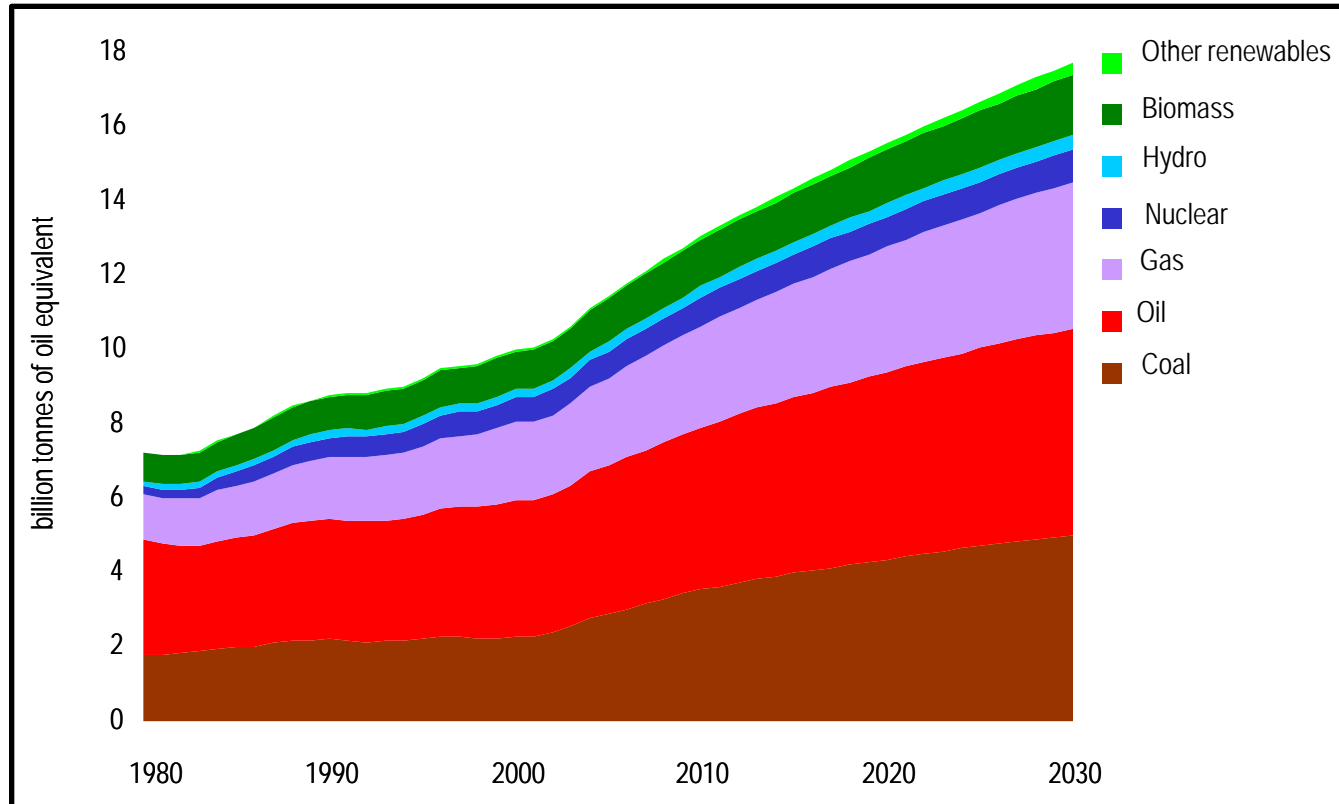
Nuværende energikilder (2005)

- De fossile kilder: kul, olie og naturgas dækker ca. 80%
- De vedvarende kilder: vind, sol, vandkraft og biomasse dækker ca. 15%
- Atomkraft dækker ca. 5%





Fossil energy use is increasing



- **Heading for trouble!**

Alternative energikilder uden udledning af CO₂

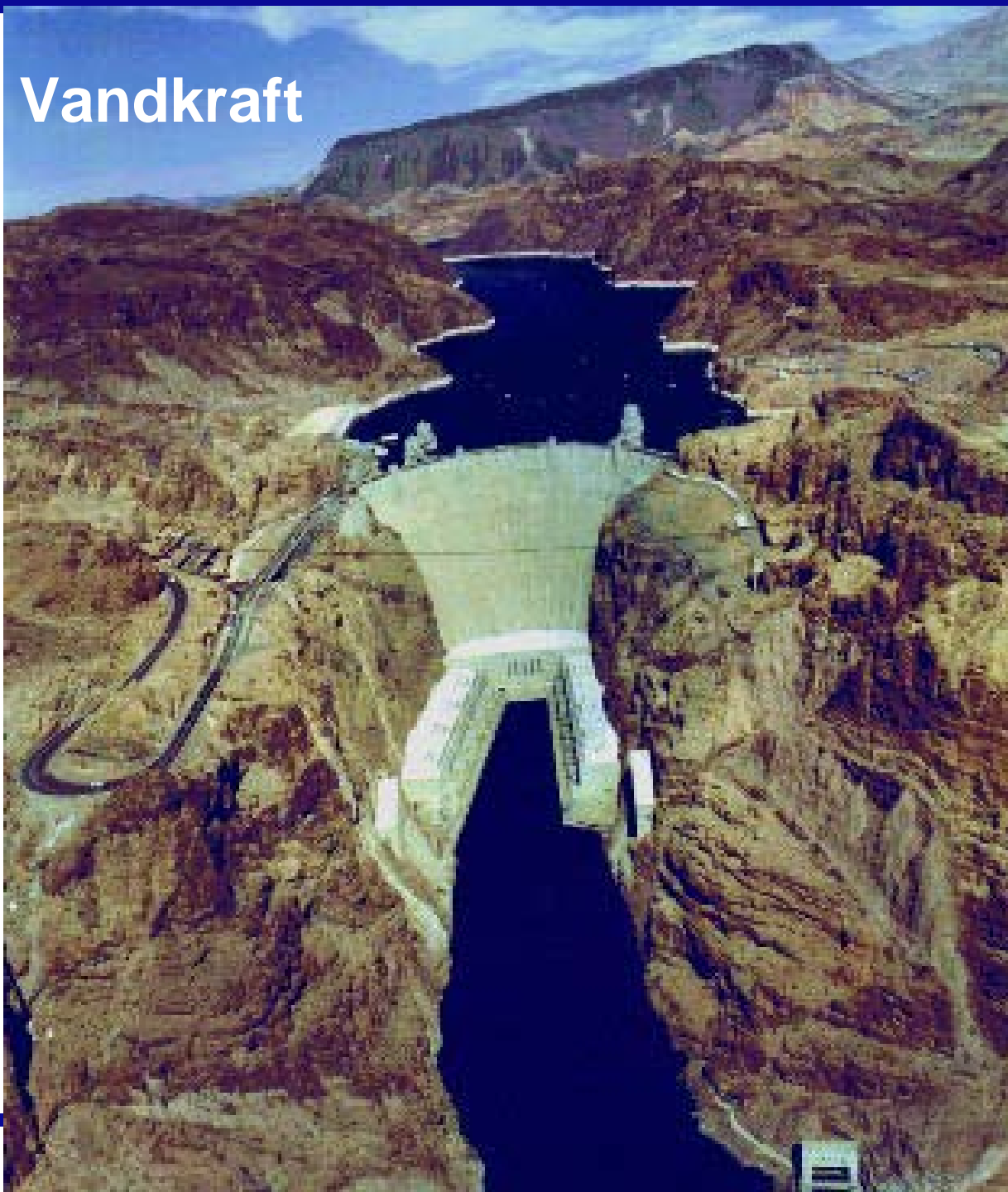


Vindkraft

Middelgrunden 20X2 MW

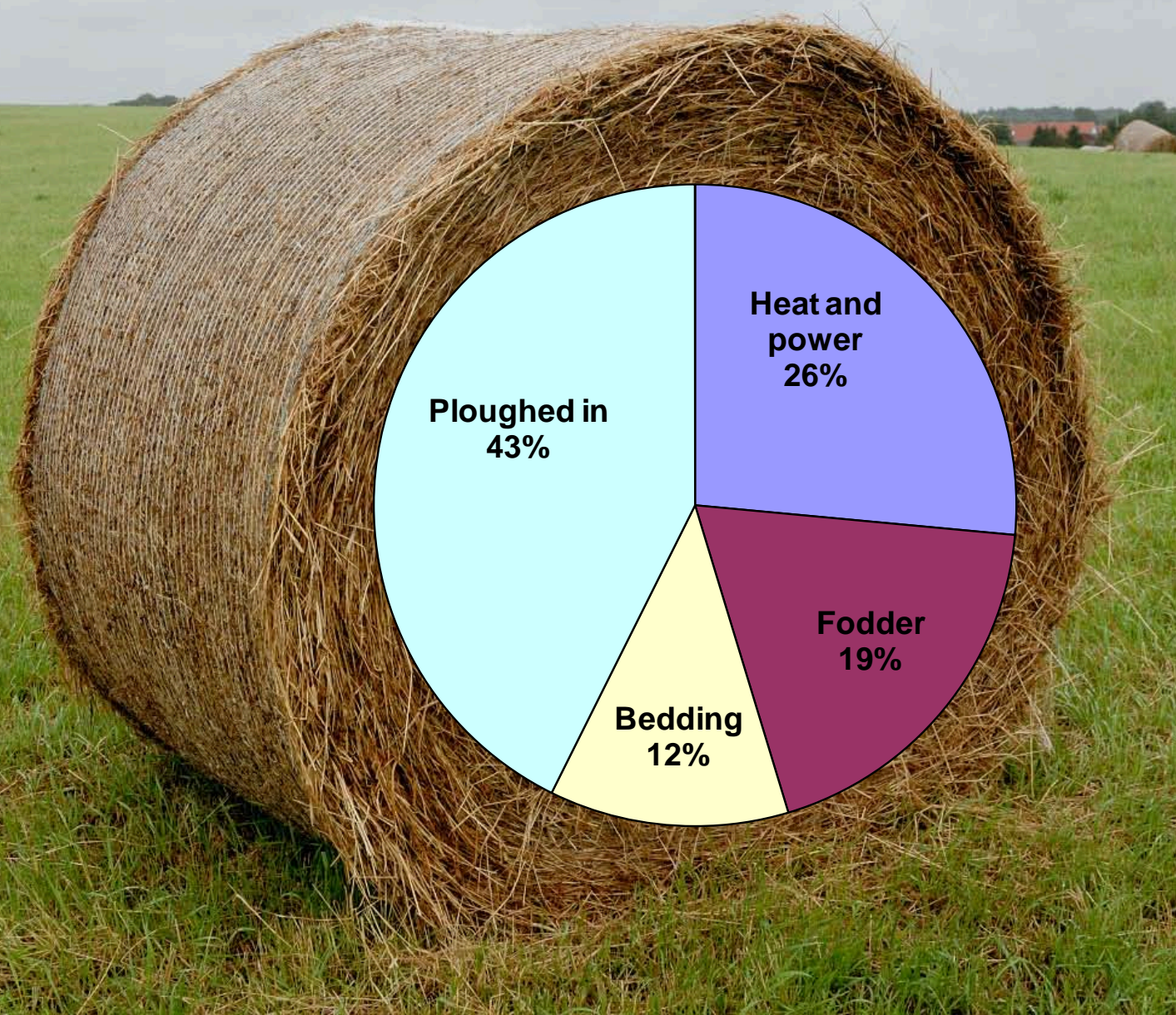


Vandkraft

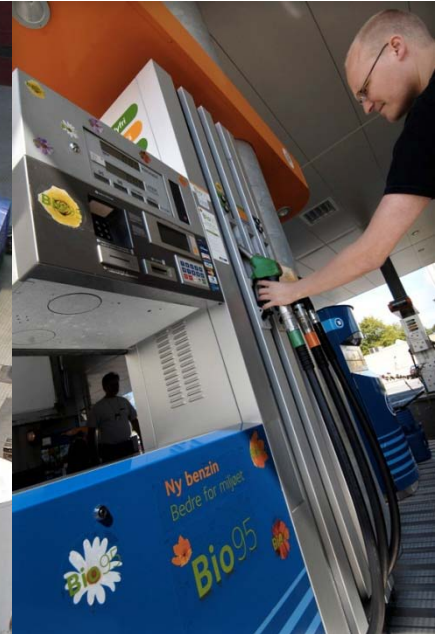


Biomass resources

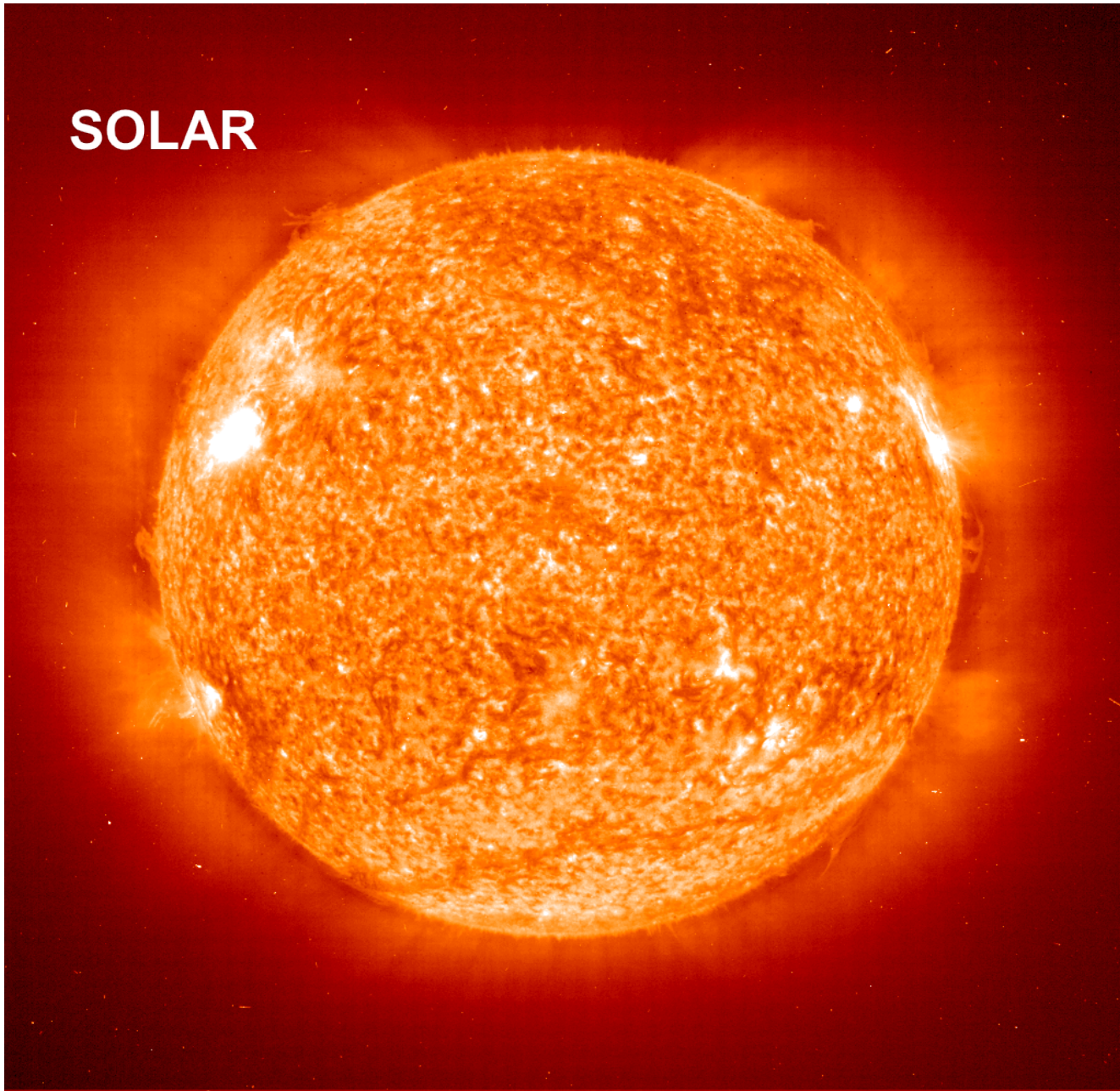
Straw: 5.2 mill. tons (2006)



Biomass, bio energy and bio materials



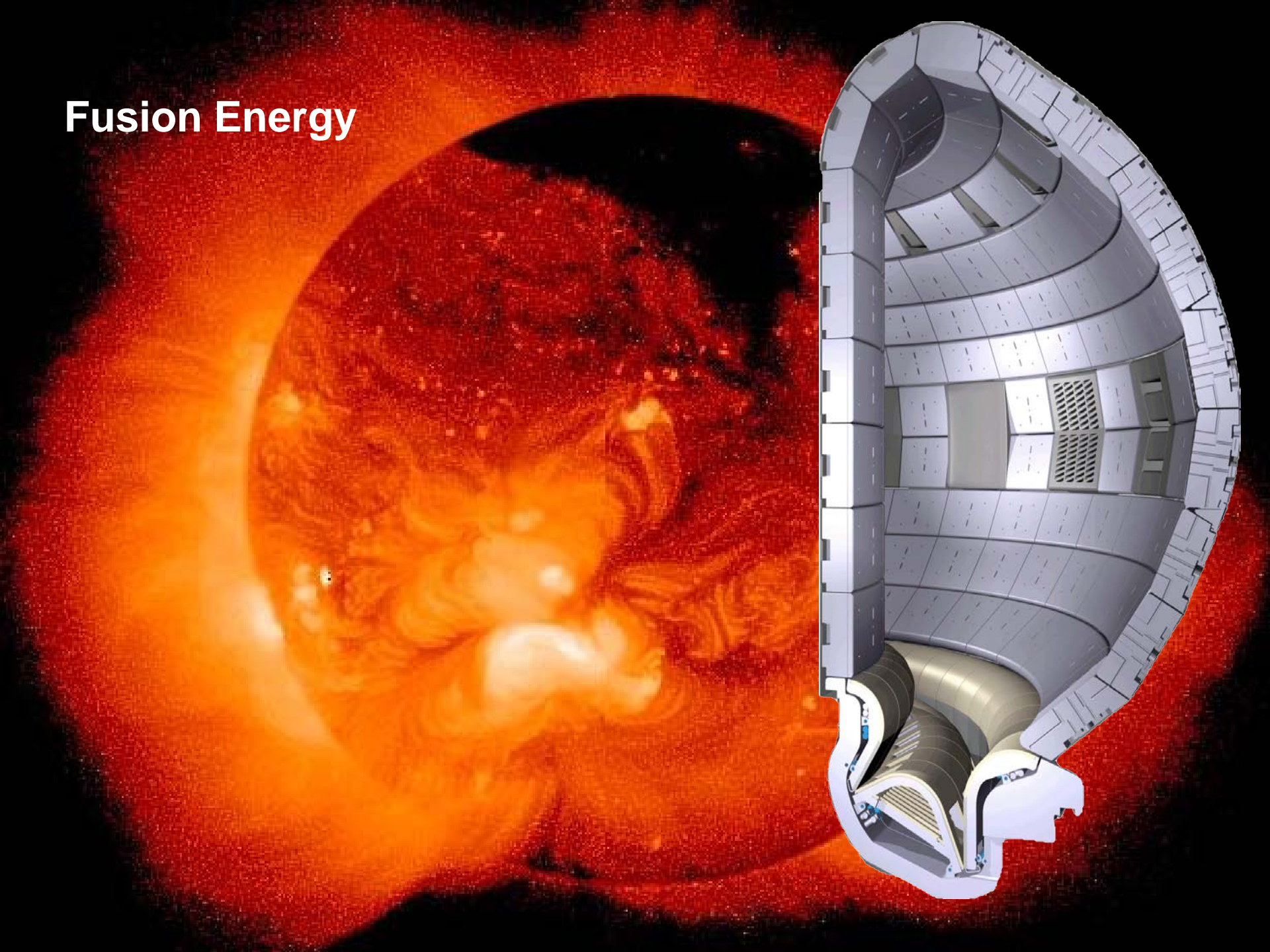
SOLAR



A solar cell made from polymers and produced by printing technology

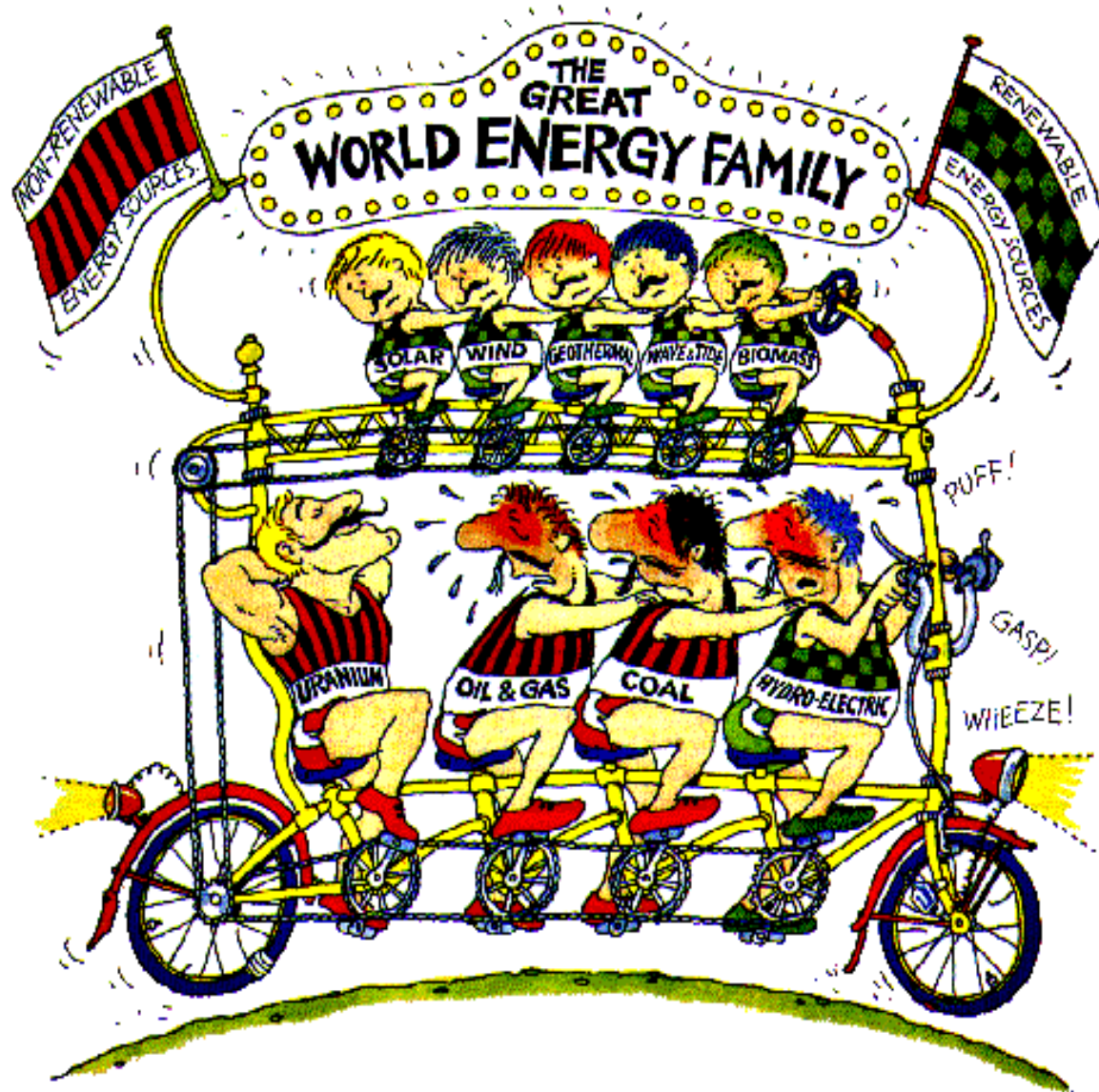


Fusion Energy

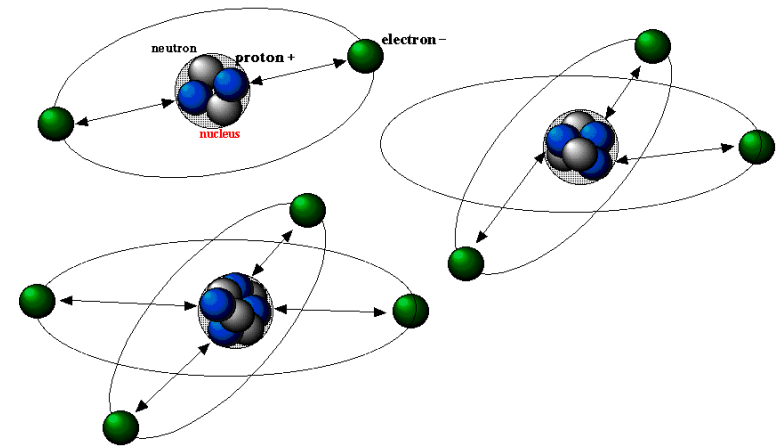
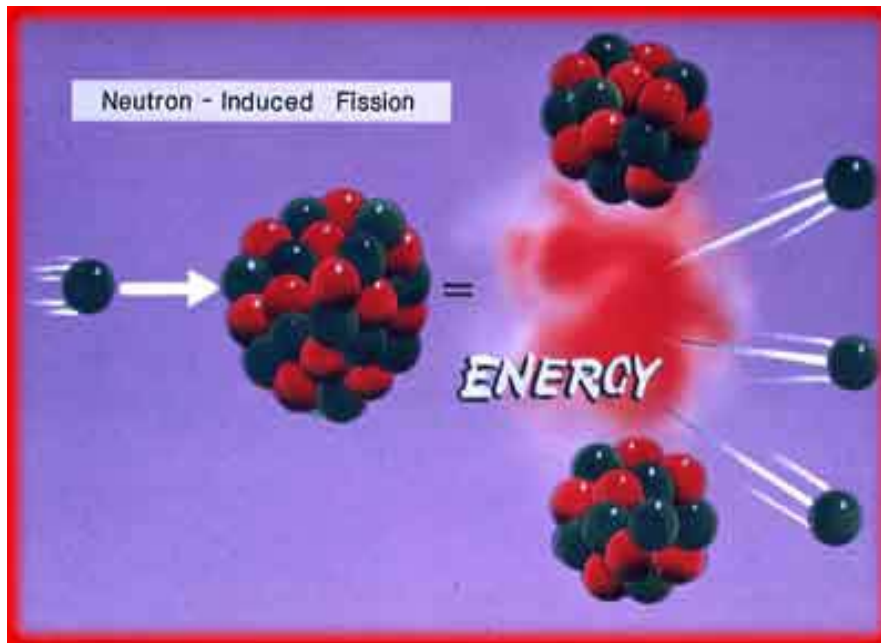


Nuclear Power



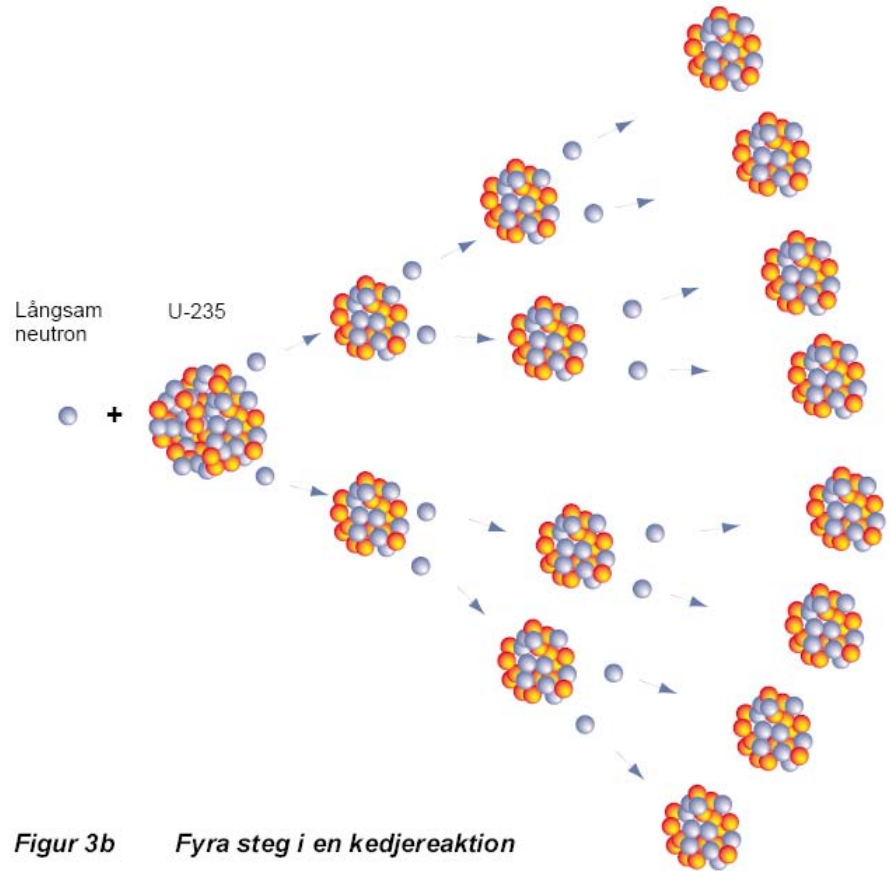
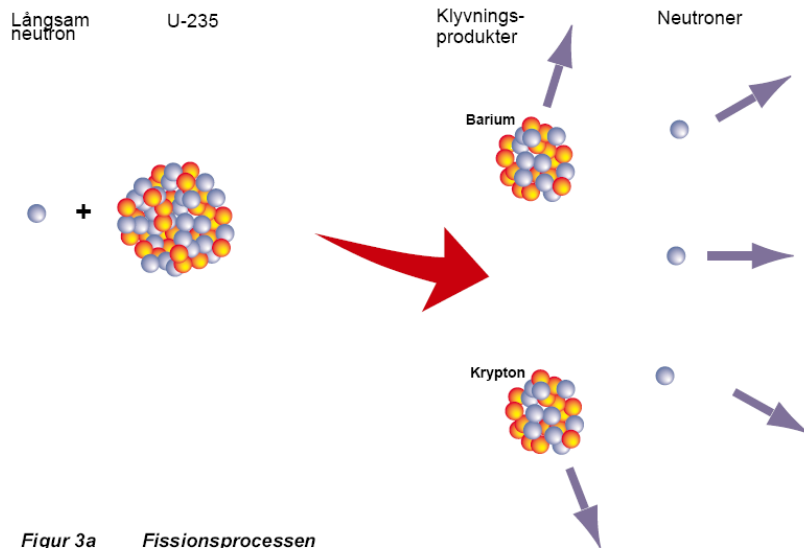


Kernkraft: Spaltning af uran (fission)



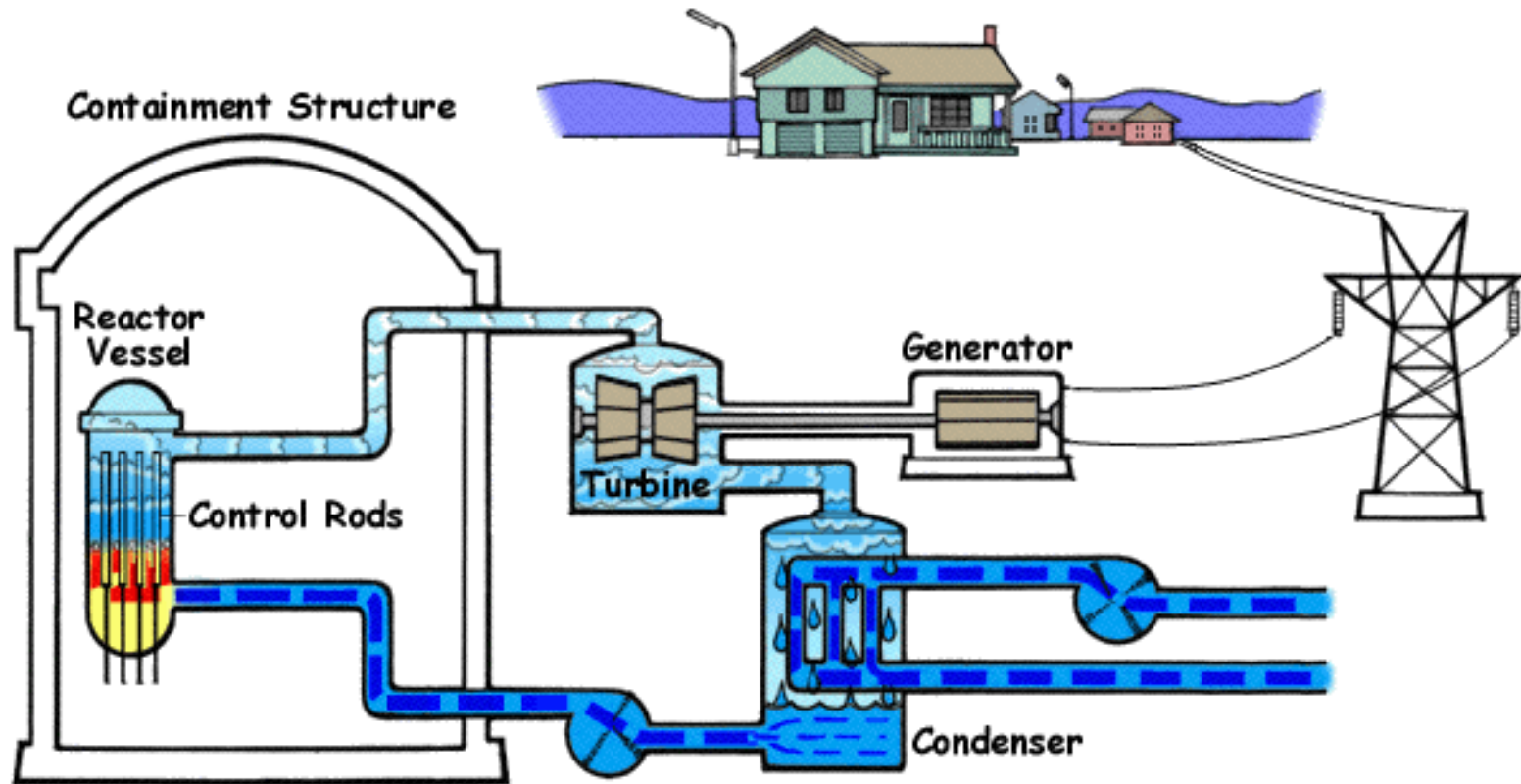
En million gange mere energi end i kul!

Kædereaktion og kritikalitet



Kædereaktion

Boiling Water Reactor - BWR



For at erstatte en reaktor i Forsmark...



Forsmark 1

Elektrisk effekt: 980 MW

1,3 millioner hestekræfter

20 tons uranbrændsel/år

For at erstatte en reaktor i Forsmark kræves



Vindkraft

1000 vindmøller
(på 2 MW)



Biobrændsel (træflis)

16,5 millioner m³

Stenkul

Tre millioner ton



Vandkraft



Udbygning af
Torne og Kalix elv

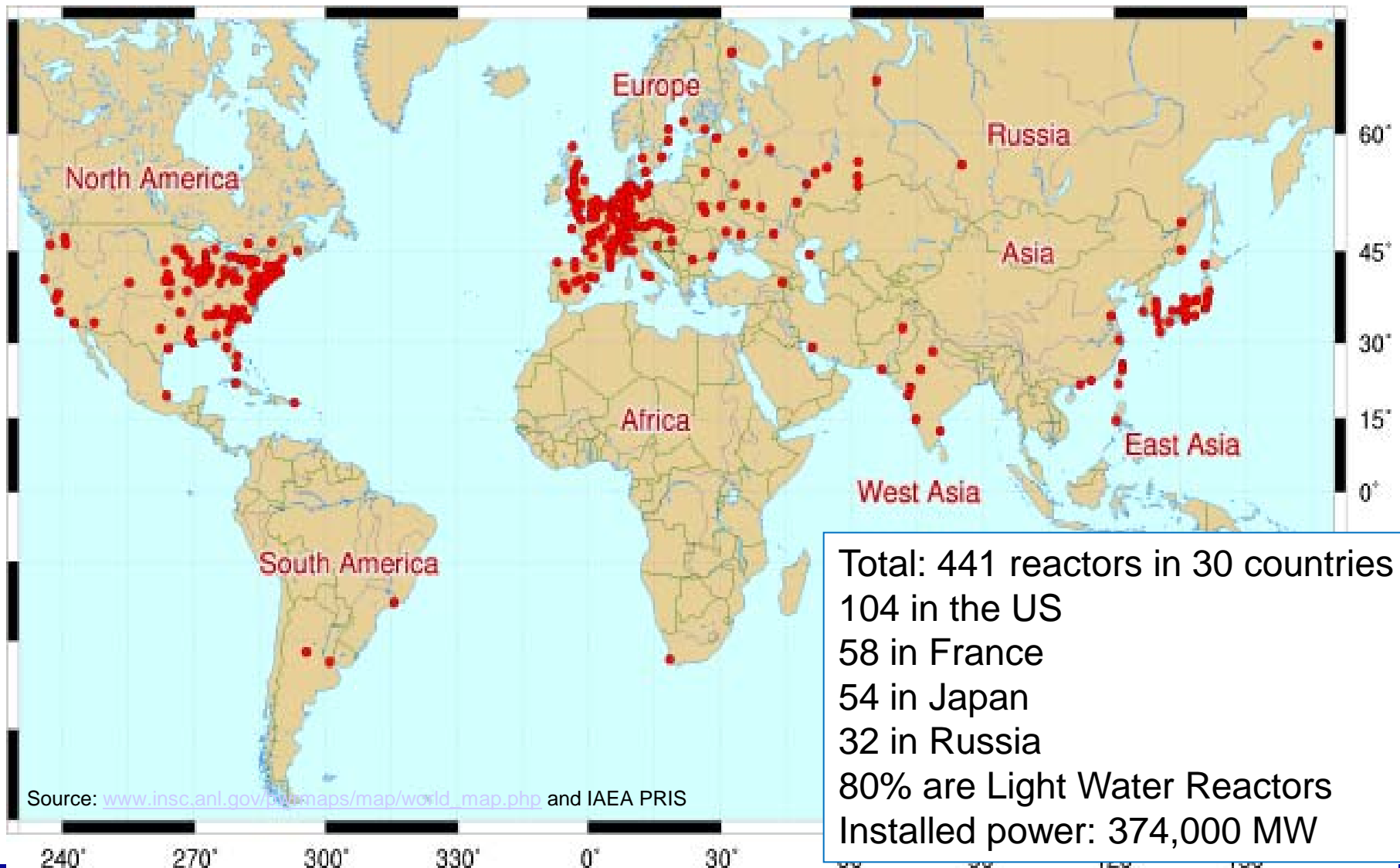


Naturgas eller olie

Gas: 2,1 milliarder m³

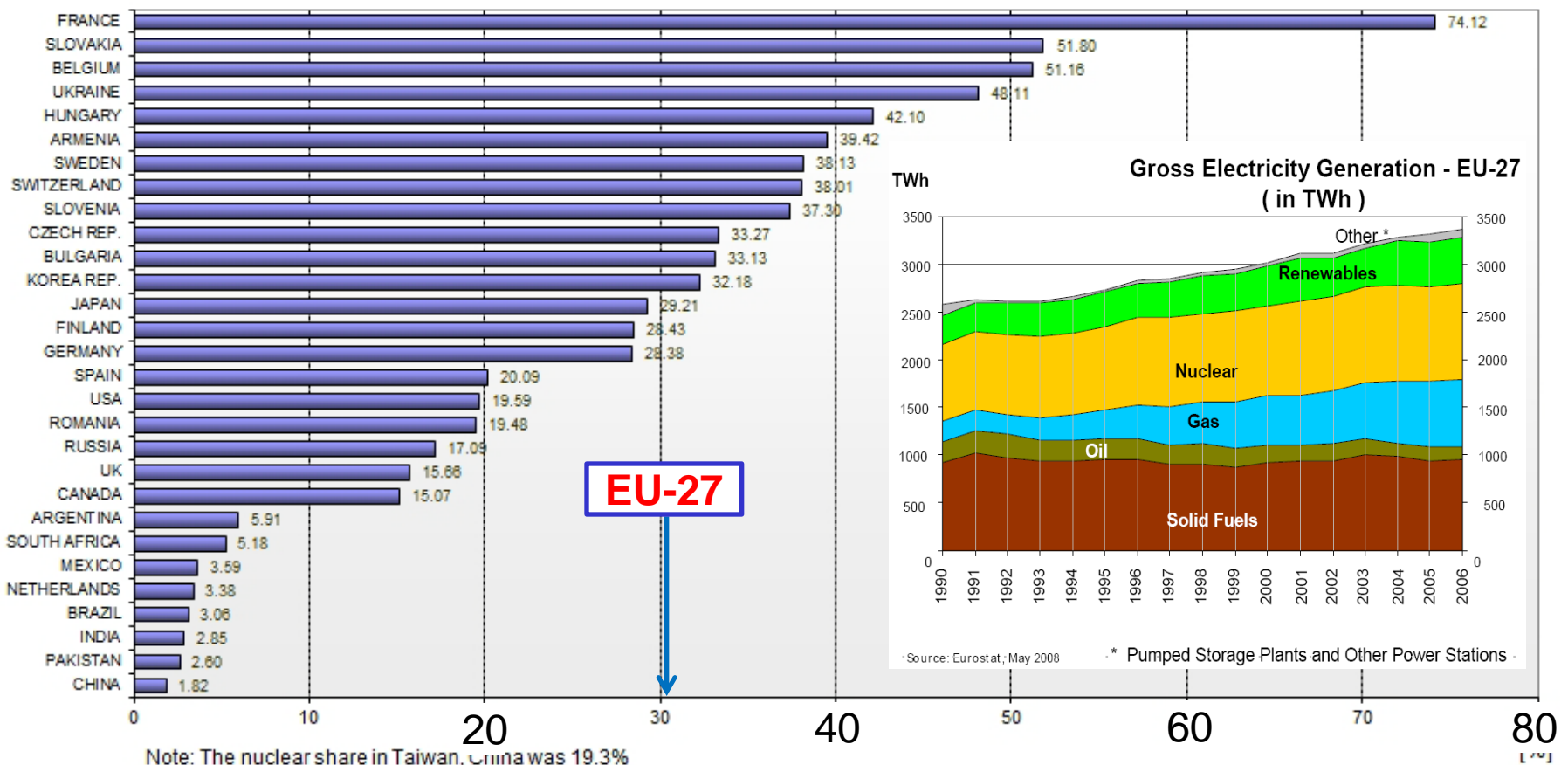
Olie: 2,1 millioner m³

Nuclear Power Plants in the World



Nuclear Share of Electricity Generation

Nuclear Share in Electricity Generation in 2010



Nuclear renaissance?

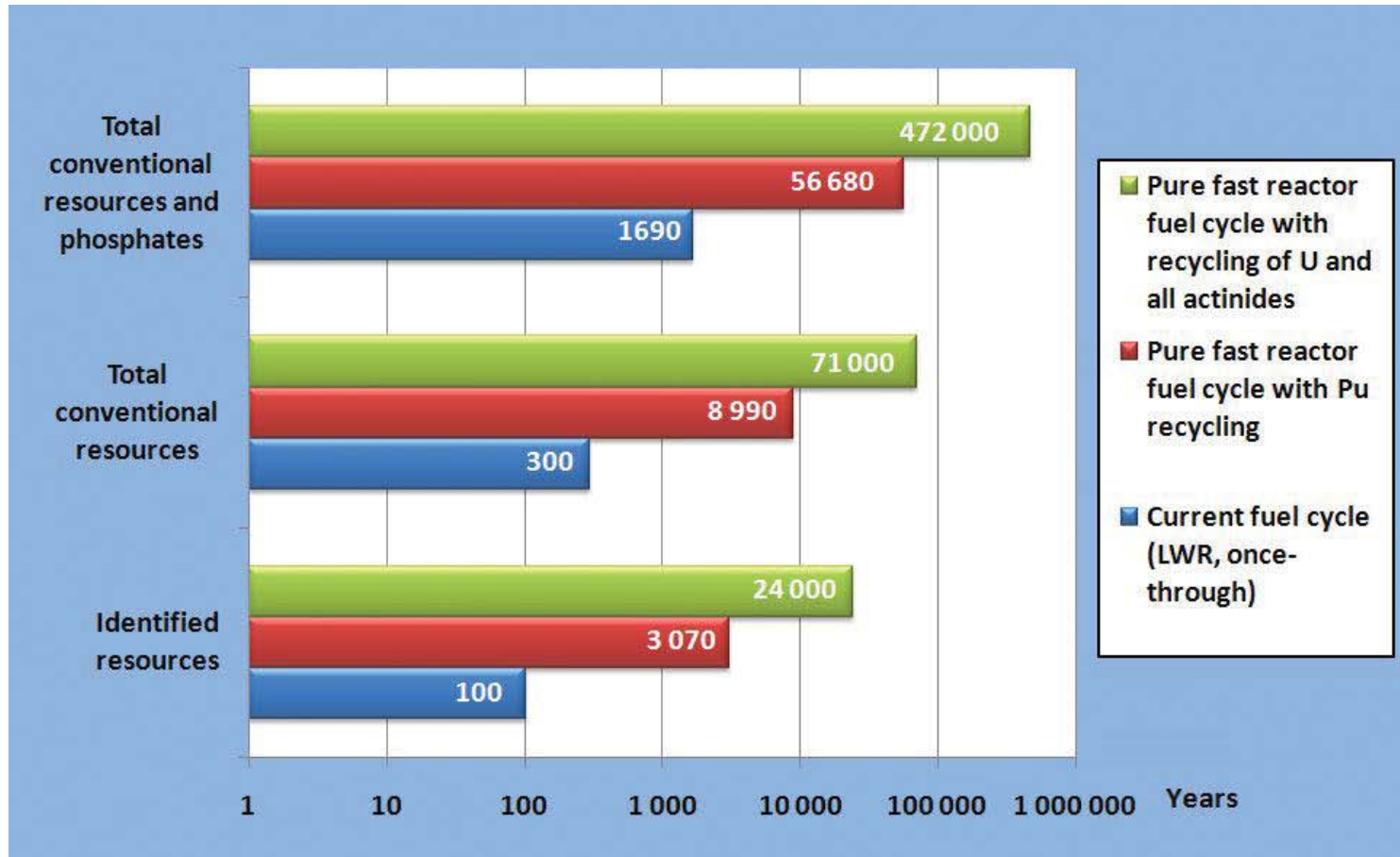
Opportunities

- Security of supply
- Environmental issues
- Economy

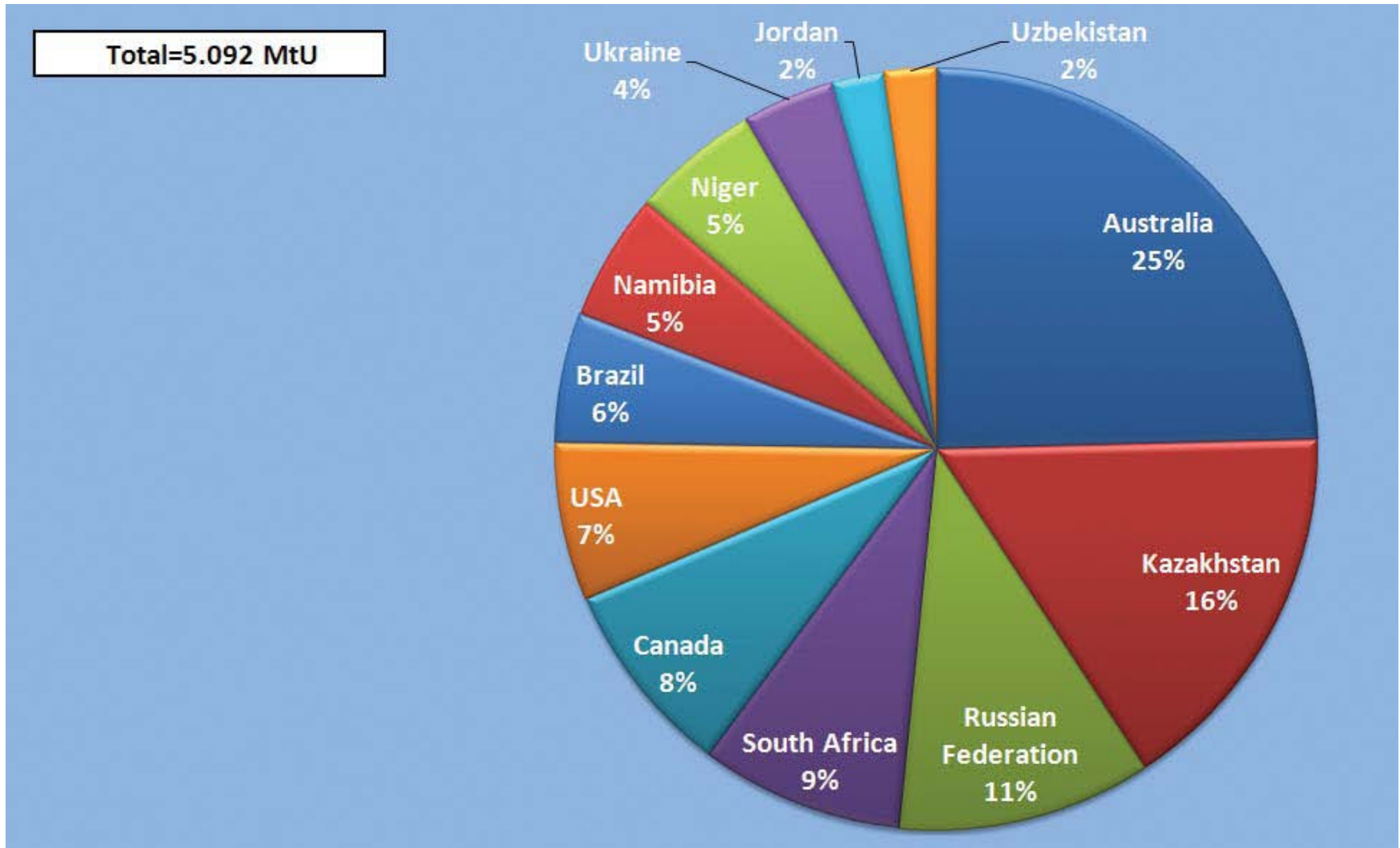
Challenges

- Safety of nuclear power
- Waste management
- Proliferation issues
- Public acceptance

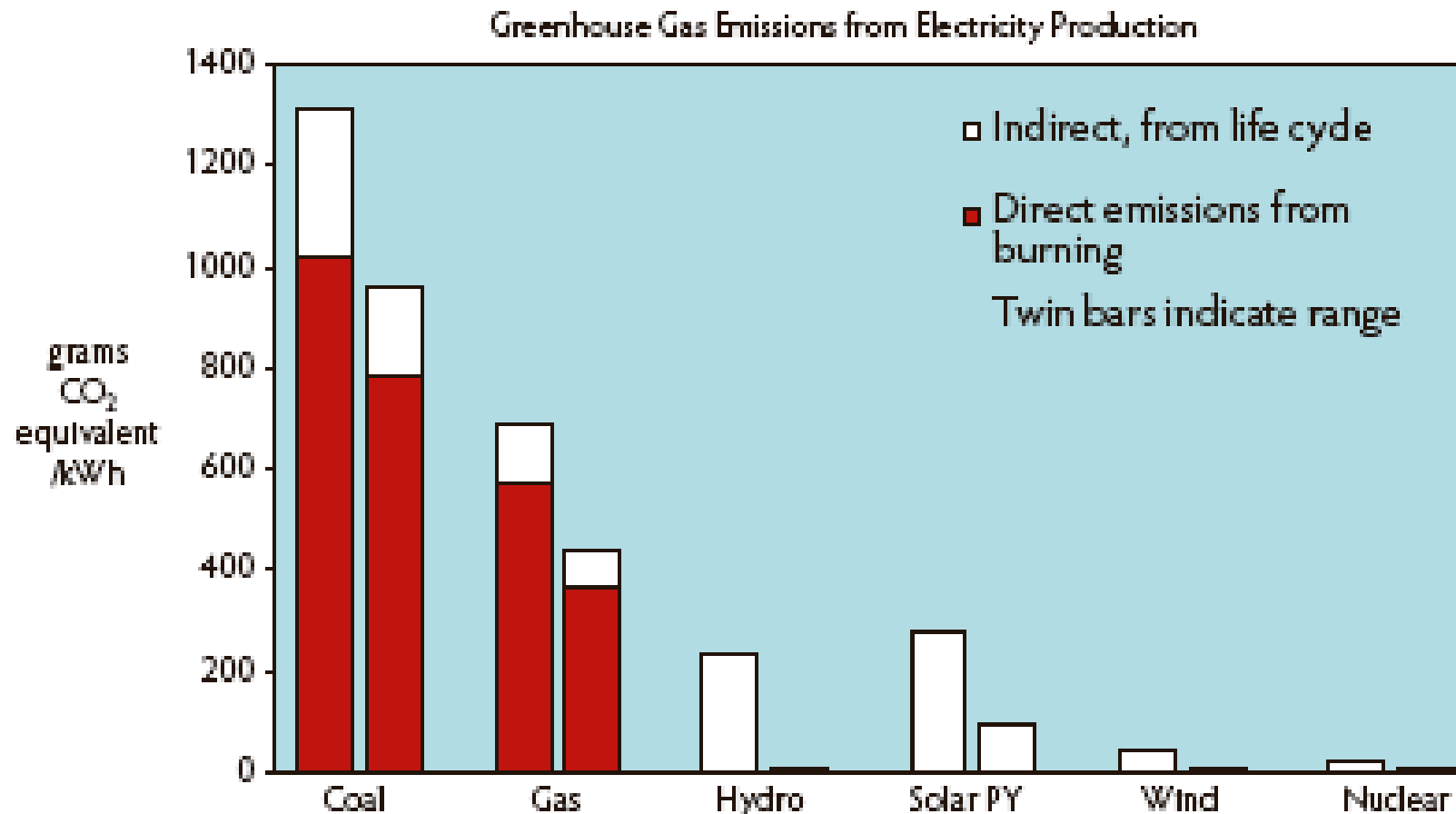
Security of supply – Uranium resources



Uranium resources are distributed



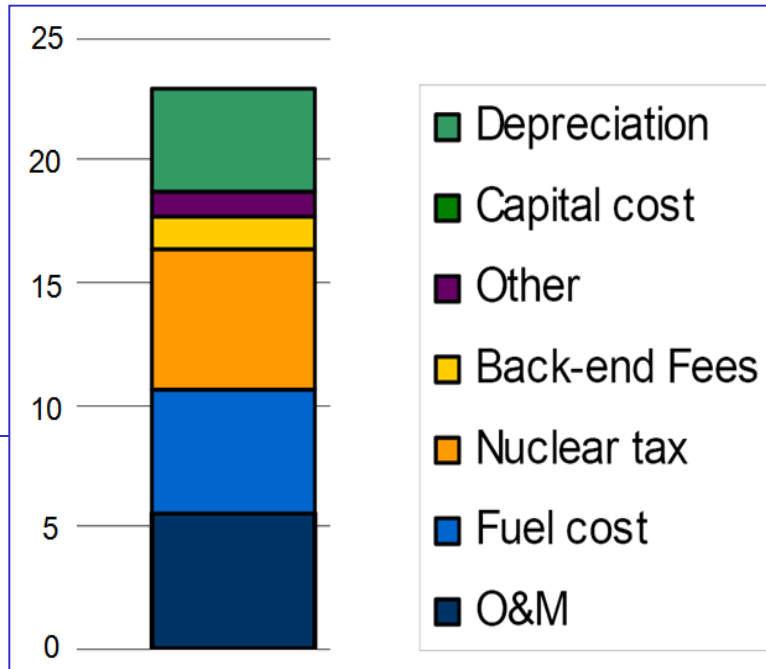
Nuclear has a low carbon footprint



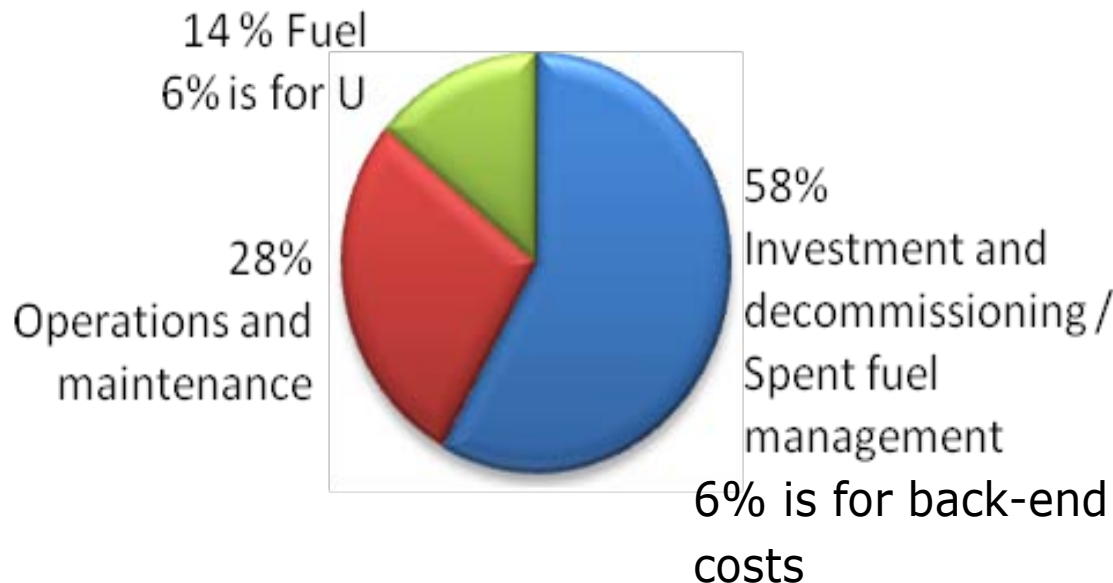
Source: IAEA 2000

Costs of Nuclear Energy Production

*Typical Swedish Cost Distribution
(öre/kWh)*



Typical International Cost Distribution



Nuclear renaissance?

Opportunities

- Security of supply
- Environmental issues
- Economy

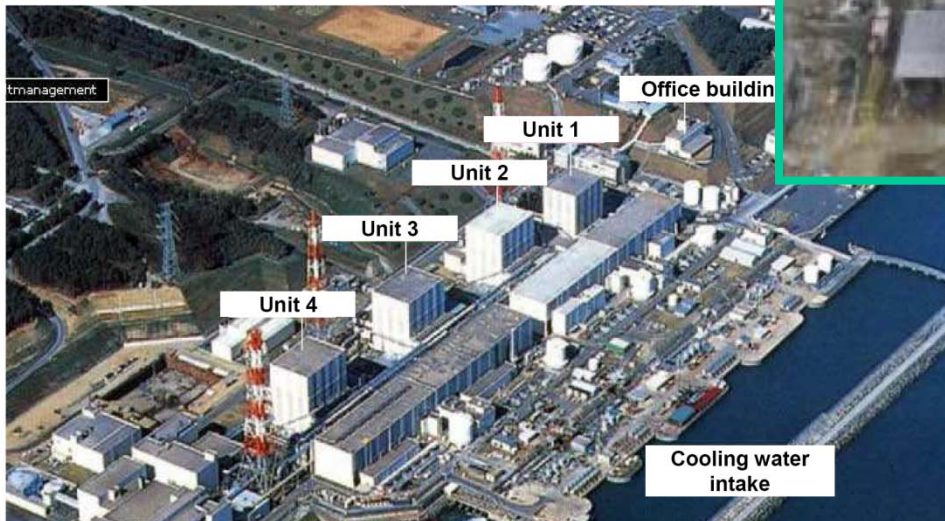
Challenges

- Safety of nuclear power
- Waste management
- Nuclear weapons
- Public acceptance

Sikkerhed ved kernekraftværker

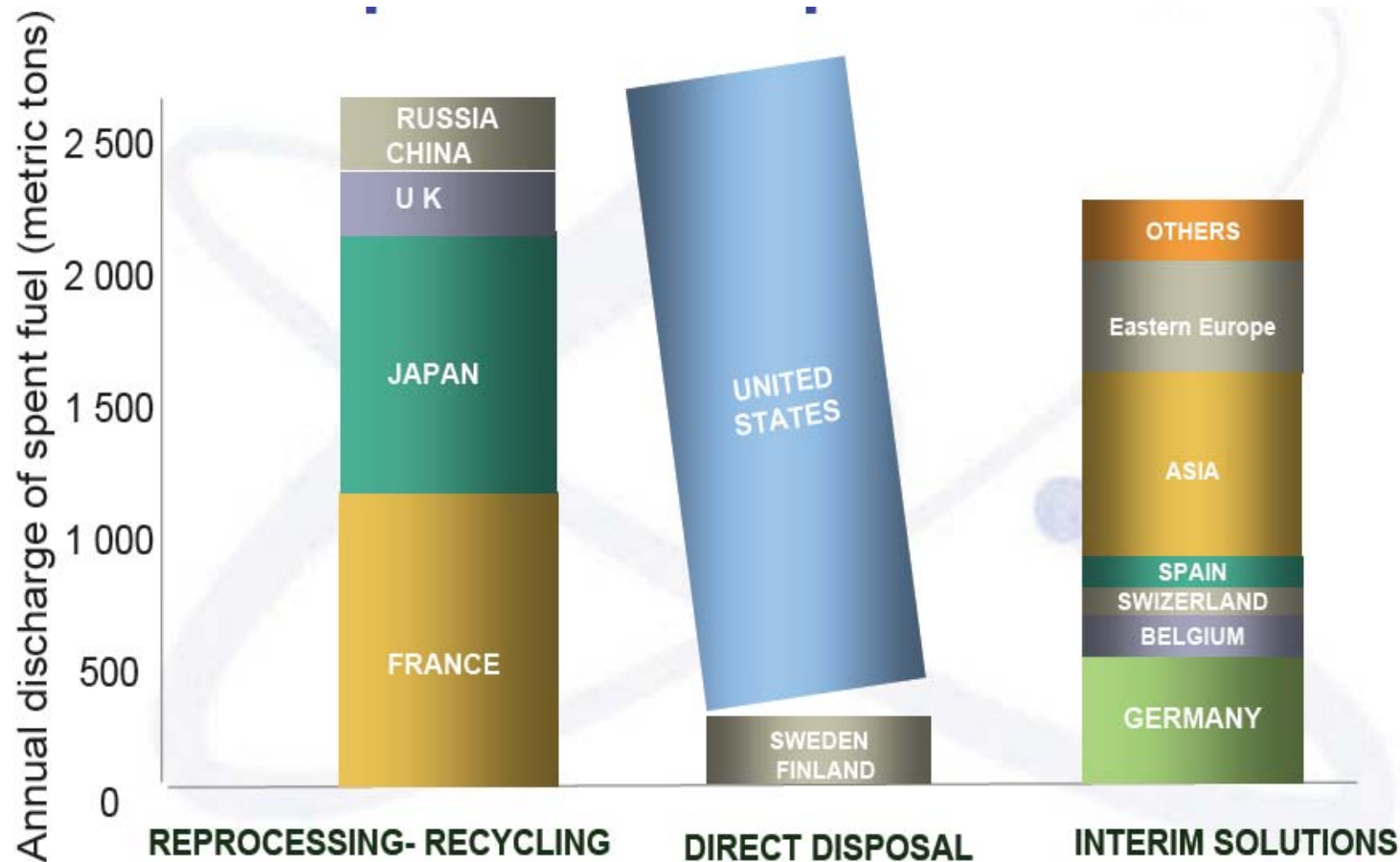
- Fukushima 2011

► Fukushima Daiichi (Plant I)



Waste Handling and Storage

- Waste handling approach varies between countries – reprocessing requires large scale investments





Nuclear weapons – a security challenge

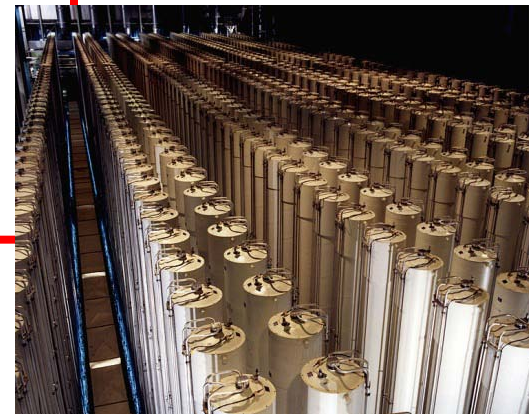
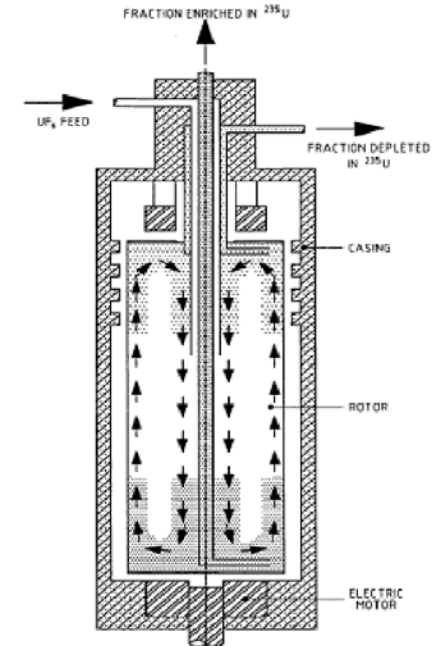
Nuclear power technologies:

- Enrichment of uranium: U-235
- Reprocessing spent fuel for plutonium

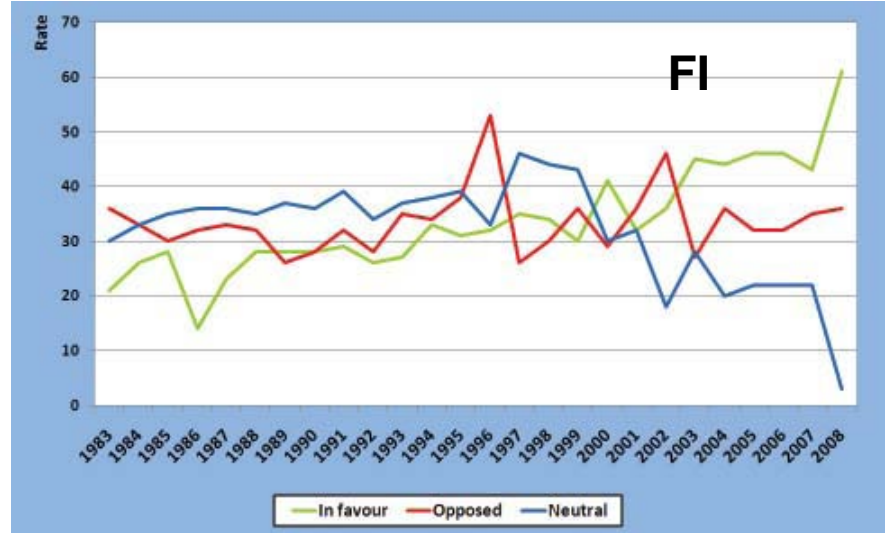
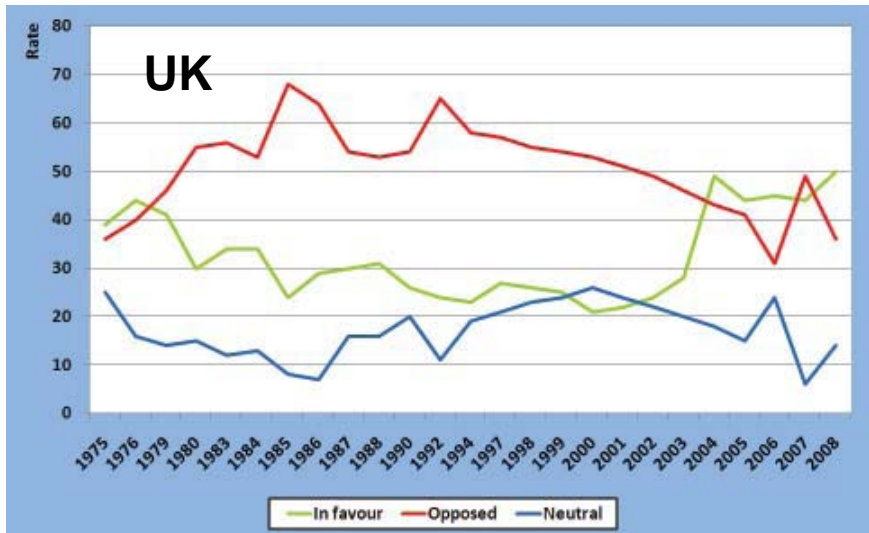
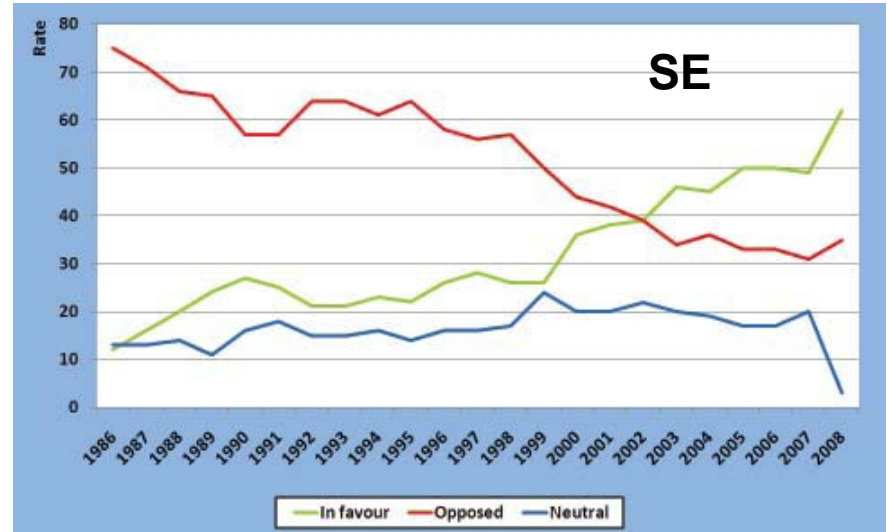
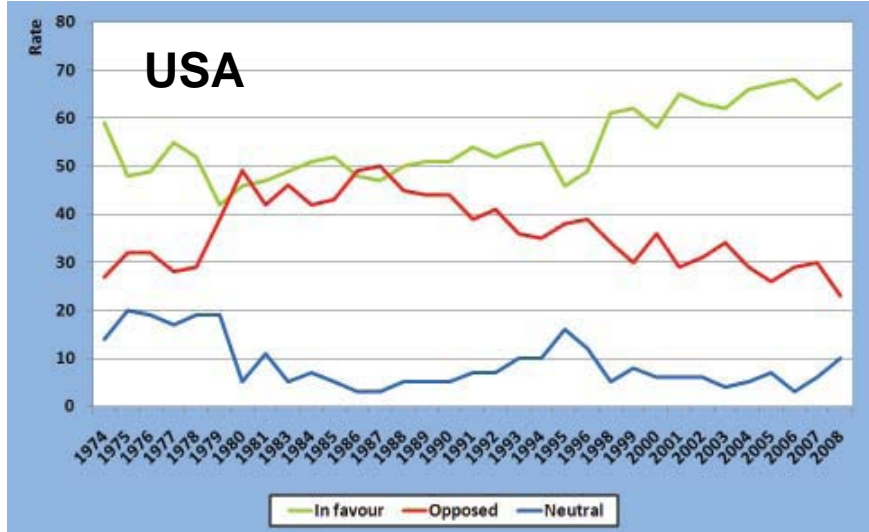
May also be used for nuclear weapons!!!

International Atomic Energy Agency (IAEA)

- Non-proliferation treaty
- Safeguard of fissile materials



Public opinion – in favor of nuclear?

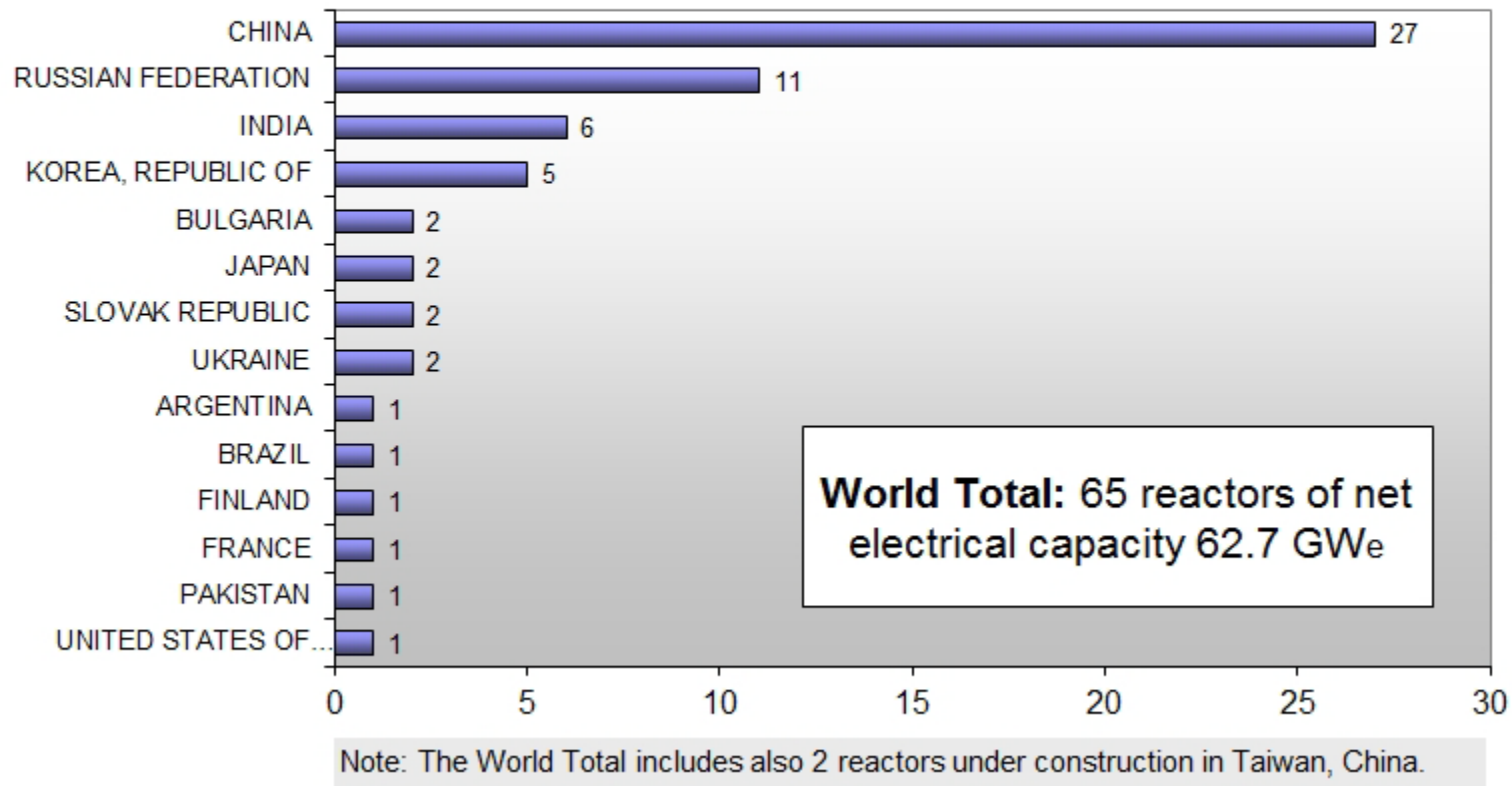


The Near Future

**More than 60 New Nuclear Power Plant
Builds in Progress and Another Close to
100 are Planned**

Nuclear power plants information

Number of Reactors under Construction Worldwide

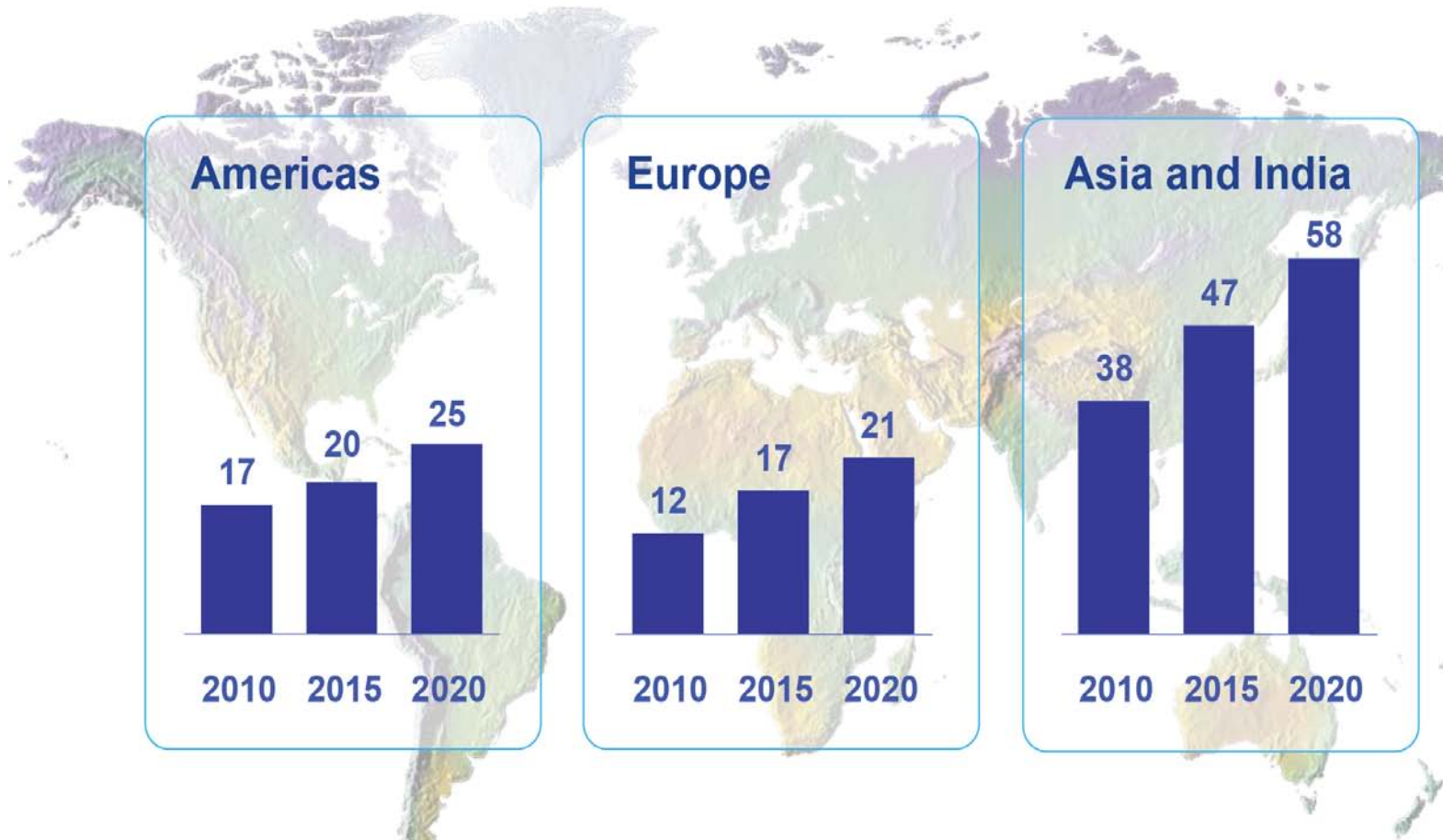


Source: © 2009 IAEA

Planning of New Nuclear Power Plants

New Construction Forecasts ...

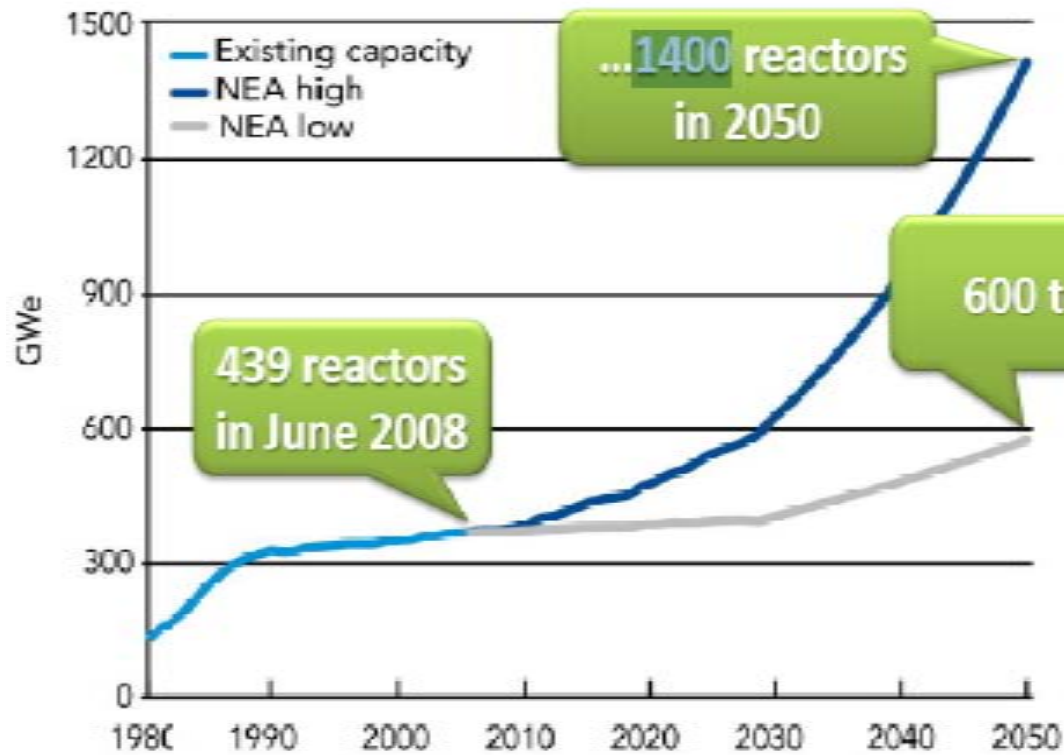
(Orders; GW Cumulative)



In September 2011, 63 power reactors are under construction in 14 countries

Past and future development

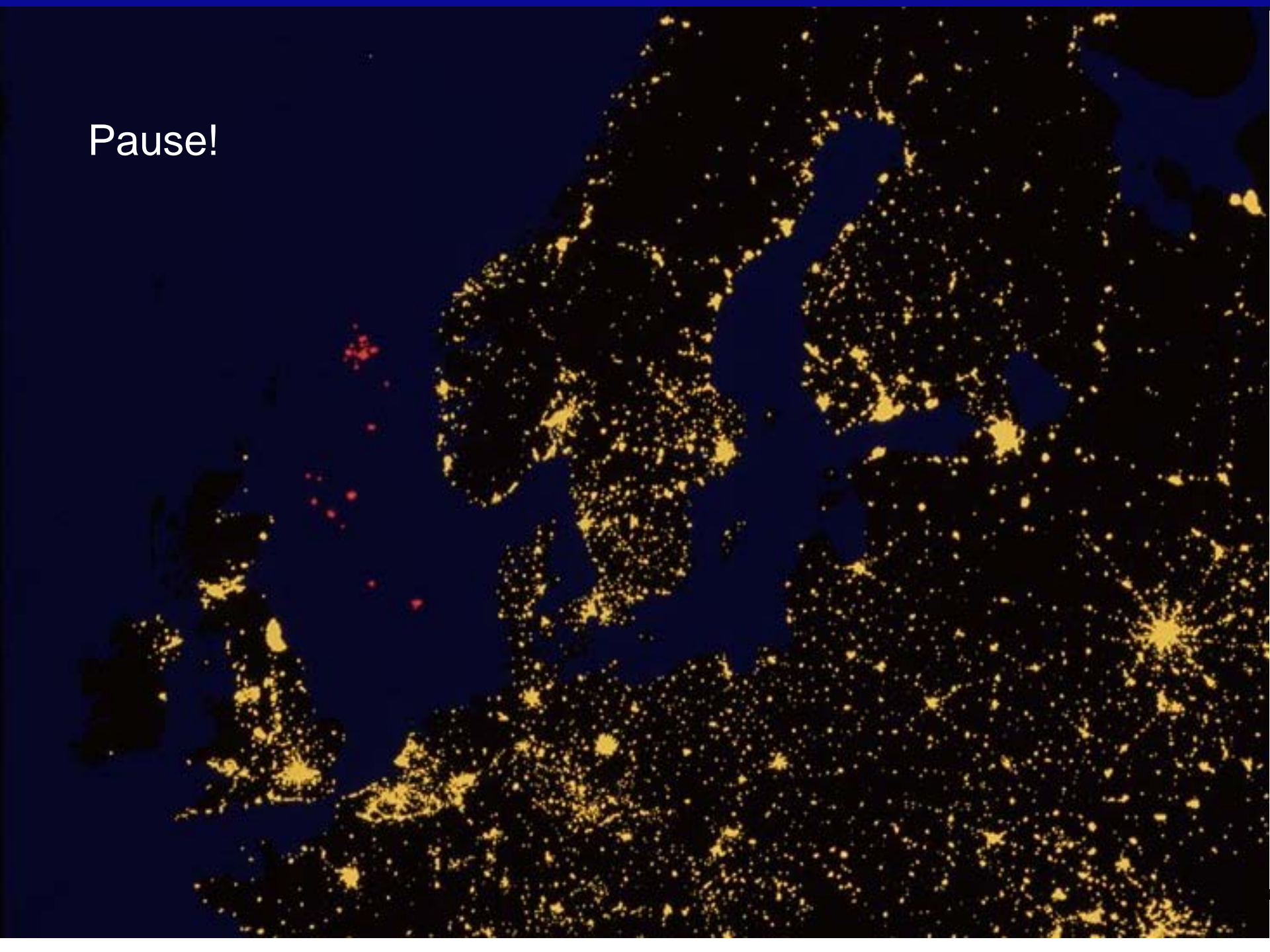
Nuclear power could expand by a factor of almost 4



Also after Fukushima?

Source: OECD/NEA

Pause!



Fukushima

status for en igangværende ulykke

IDA 18 maj 2011

+

Opdateringer frem til 10. september 2011

Erik Nonbøl, Risø DTU

Steen Hoe, Beredskabsstyrelsen

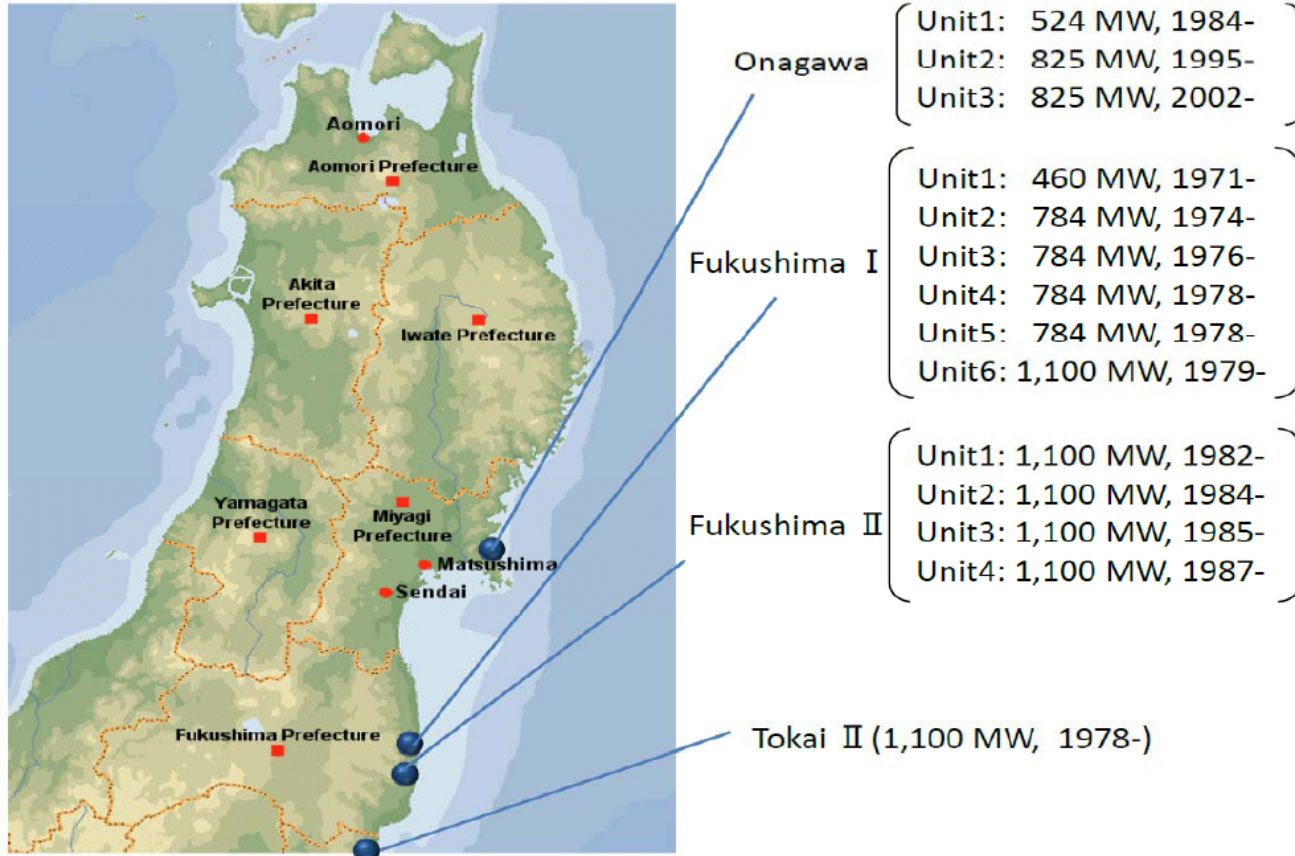
Japanske reaktorer tæt på epicentret

11. marts, lokal tid 14:46, gmt 06:46



1-3. Nuclear reactors near epicenter of the earthquake

Location of the Nuclear Installations



5

2-1. Summary of Fukushima Dai-ichi NPS

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
	BWR-3	BWR-4	BWR-4	BWR-4	BWR-4	BWR-5
PCV Model	Mark-1	Mark-1	Mark-1	Mark-1	Mark-1	Mark-2
Electric Output (MWe)	460	784	784	784	784	1100
Max. pressure of RPV	8.24MPa	8.24MPa	8.24MPa	8.24MPa	8.62MPa	8.62MPa
Max. Temp of the RPV	300°C	300°C	300°C	300°C	302°C	302°C
Max. Pressure of the CV	0.43MPa	0.38MPa	0.38MPa	0.38MPa	0.38MPa	0.28MPa
Max. Temp of the CV	140°C	140°C	140°C	140°C	138°C	171°C(D/W) 105°C(S/C)
Commercial Operation	1971,3	1974,7	1976,3	1978,10	1978,4	1979,10
Emergency DG	2	2	2	2	2	3*
Electric Grid	275kV × 4				500kV × 2	
Plant Status on Mar. 11	In Operation	In Operation	In Operation	Refueling Outage	Refueling Outage	Refueling Outage

* One Emergency DG is Air-Cooled

Automatic shut-down of nuclear reactors

● 11 reactors were automatically shut-down

- Onagawa Units 1,2,3
- Fukushima Dai-ichi (I) Units 1,2,3
- Fukushima-Dai-ni (II) Units 1,2,3,4
- Tokai Dai-ni (II)

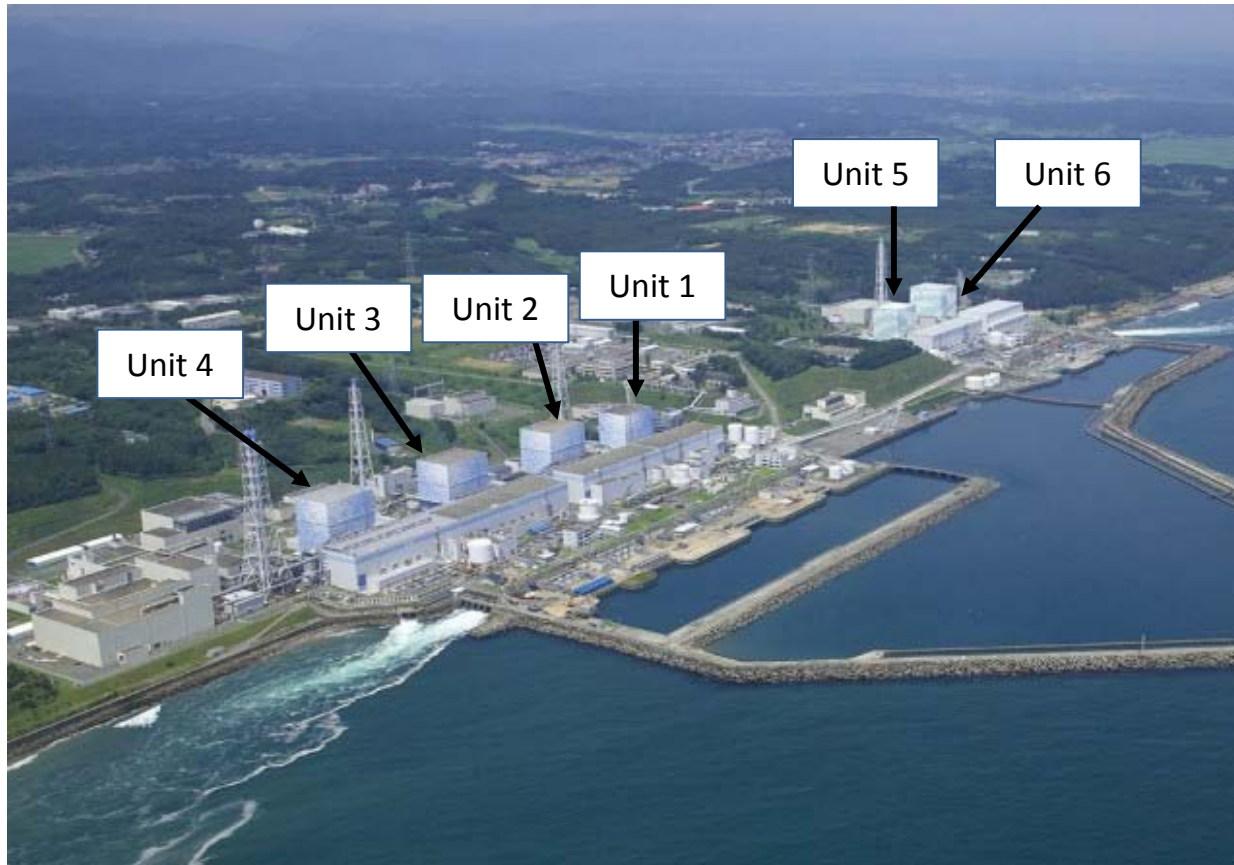
● 3 reactors were under periodic inspection

- Fukushima Dai-ichi (I) Units 4,5,6

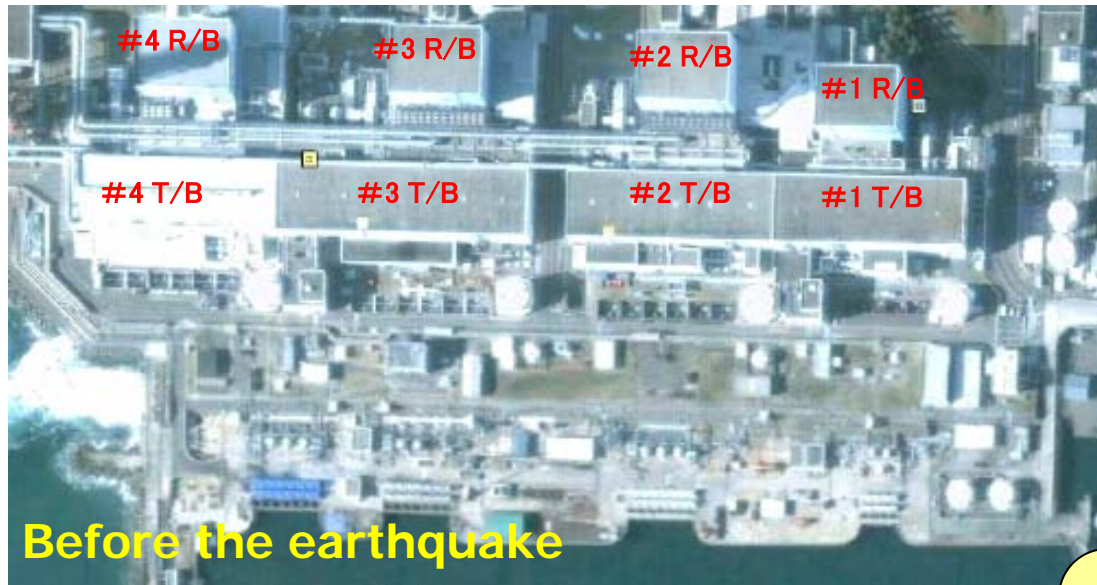
-After the automatic shut-down of, Units 1-3 at Onagawa SITE, Unit 3 at Fukushima II Site, and the Unit at Tokai II Nuclear Power Station the NPP was put in cold shut down safely.

-As for the Units 1,2,4 at Fukushima *Dai-ni* (II) Site, the operator of the station reported NISA nuclear emergency situation because the temperature of the suppression pools became more than 100 °C, but afterward the three units have been cold shut down.

Layout of Fukushima Dai-ichi Nuclear Plant Site



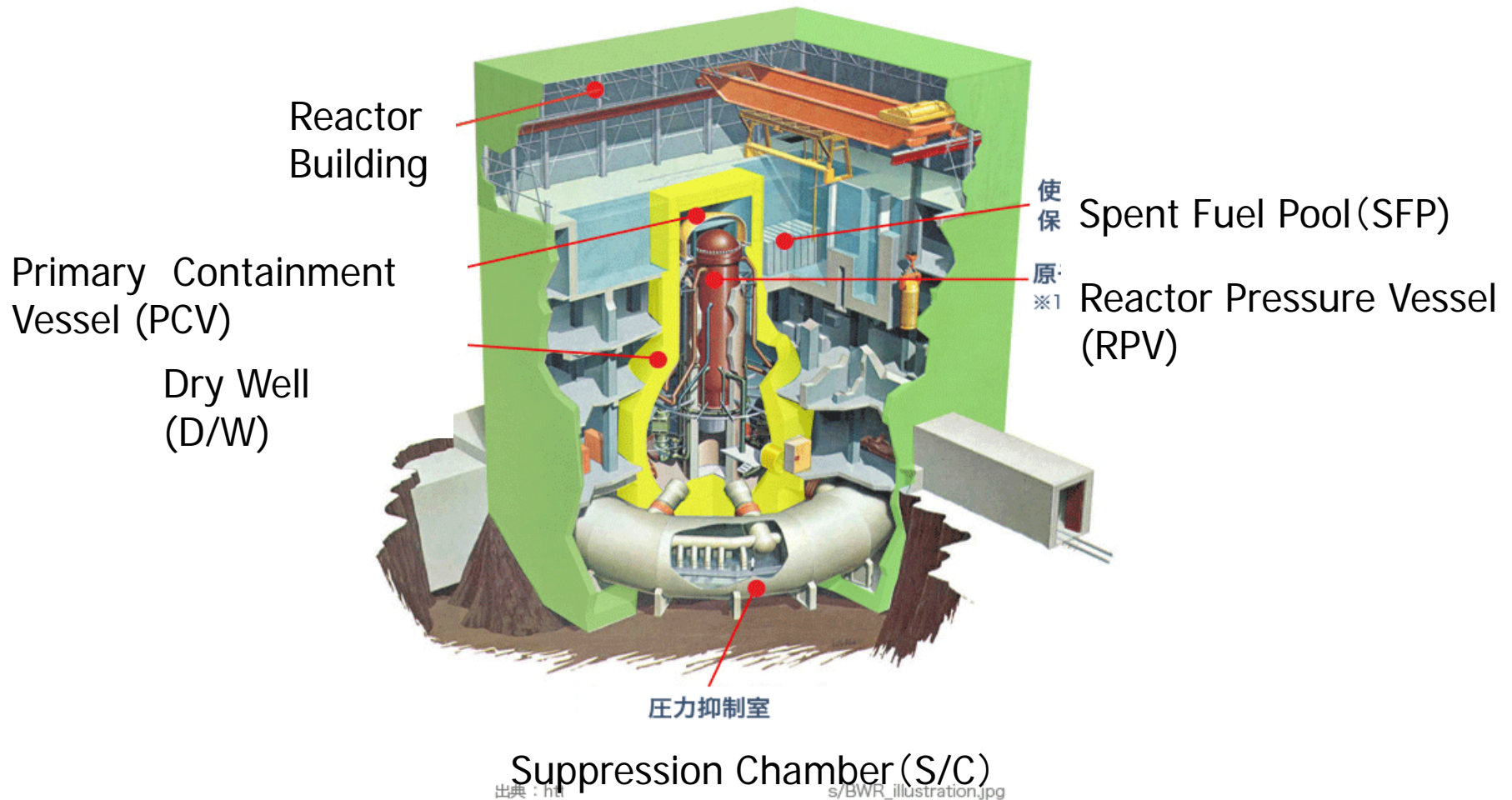
Fukushima 1 (Dai-ichi) NPP



Many
structures
facing the bay
are destroyed

Source: Google Earth

Overview of Mark-1 Type BWR (Units 1,2,3 and 4)



Unit	1	2	3	4	5	6
Number of Fuel Assembly in the Core	400	548	548	-	548	764
Number of Spent Fuel Assembly in the Spent Fuel Pool	292	587	514	1,331	946	876
Number of New Fuel Assembly in the Spent Fuel Pool	100	28	52	204	48	64
Water Volume (m ³)	1,020	1,425	1,425	1,425	1,425	1,497

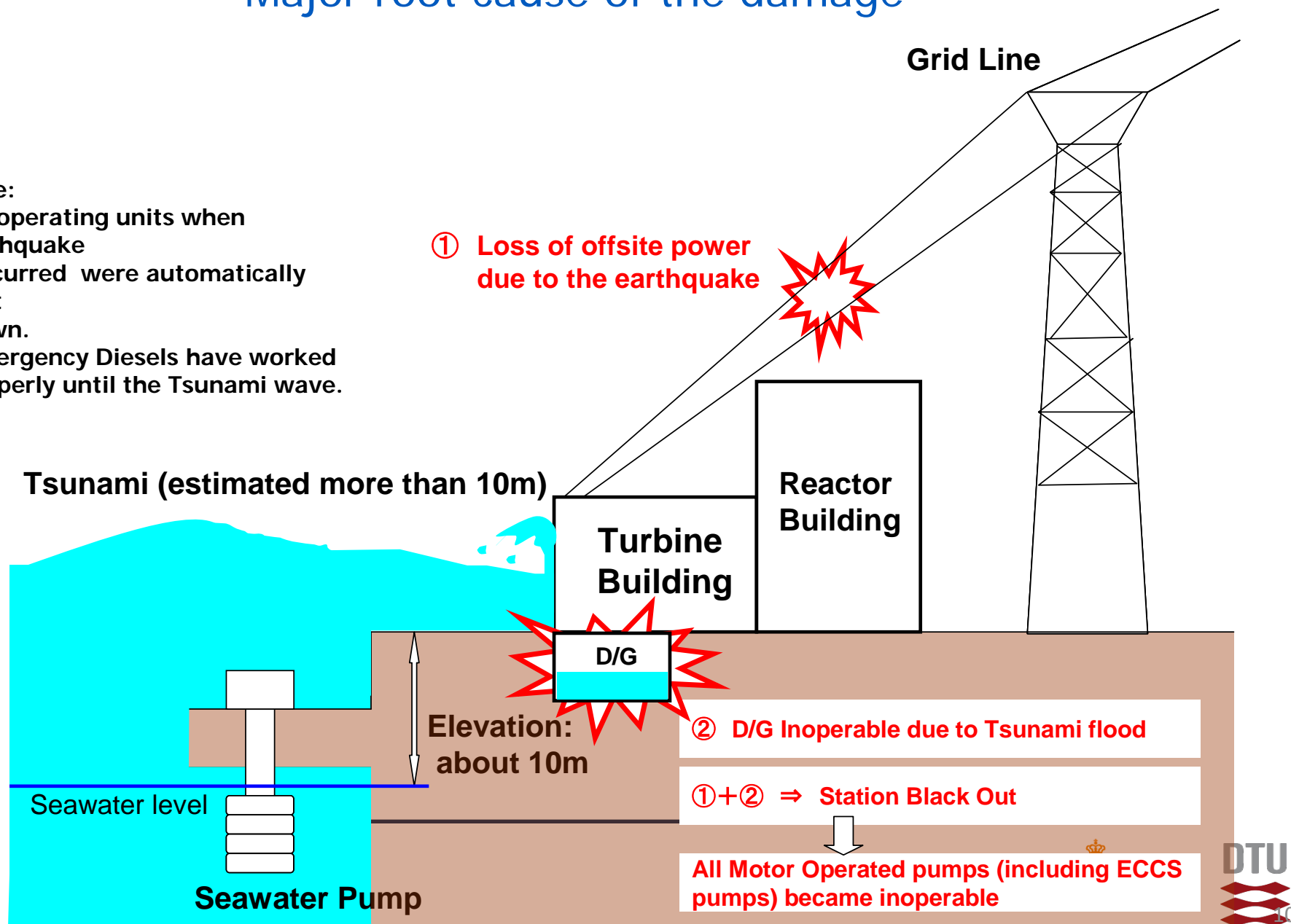
Condition of the fuel in the Spent Fuel Pool

Unit 1	Unit 2	Unit 3	Unit 4
-Most recent shut down was on Sep.27,2010	- Most recent shut down was on Nov.18,2010	- Most recent shut down was on Sep.23,2010	-Most recent shut down was on Nov.29,2010 -All fuel assembly was removed from the core and located in the pool due to the core shroud replacement

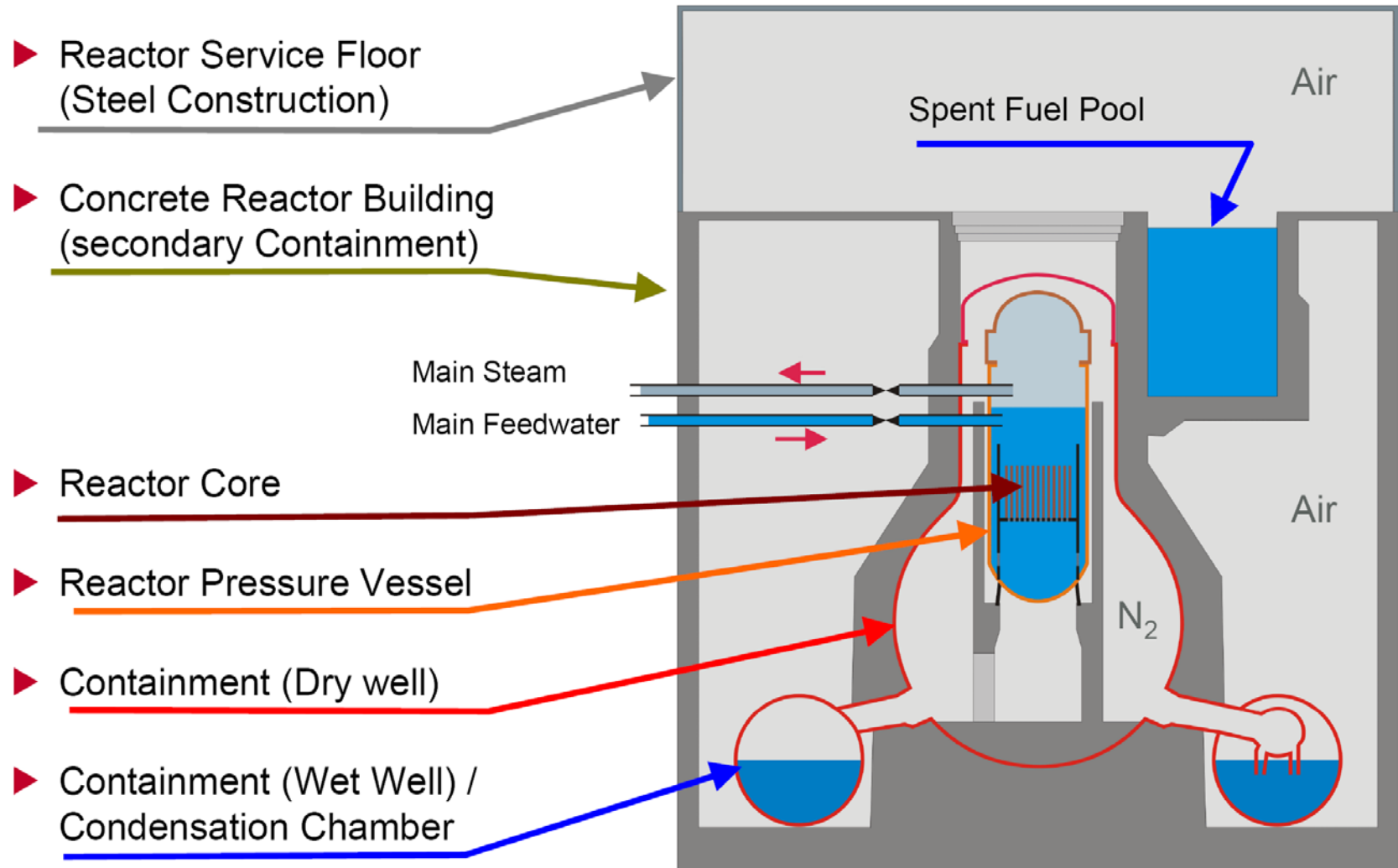
Major root cause of the damage

Note:

- All operating units when earthquake occurred were automatically shut down.
- Emergency Diesels have worked properly until the Tsunami wave.



Reactor design - Fukushima



16 May 2011

► Service Floor



16 May 2011

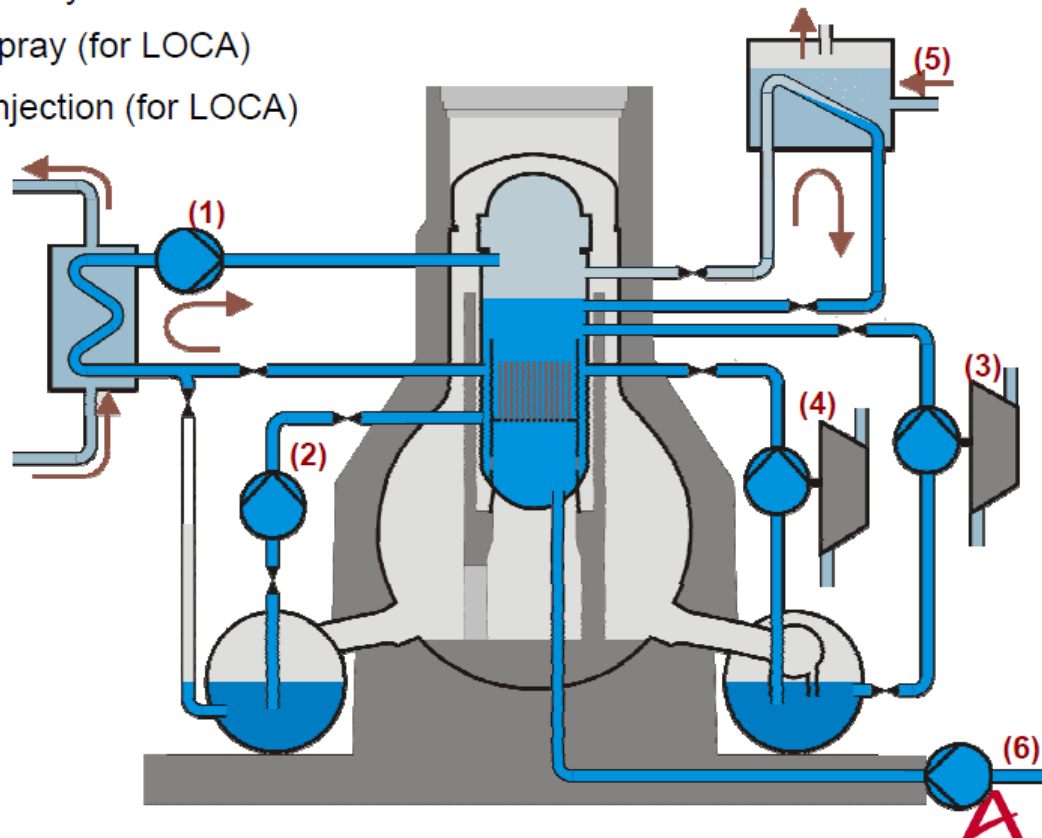
NUK seminar

1. Plant Design



► Emergency Core Cooling Systems

- 1) Residual Heat Removal System
- 2) Low-Pressure Core Spray (for LOCA)
- 3) High-Pressure Core Injection (for LOCA)
- 4) Reactor Core isolation cooling (Unit 2,3 [BWR4])
- 5) Isolation Condenser (Unit 1 [BWR3])
- 6) Borating System



ENEF special risk working group on the subject "safety of nuclear facilities" – Uwe Stoll – Brussels, 24.03.2011 - p.9

AREVA

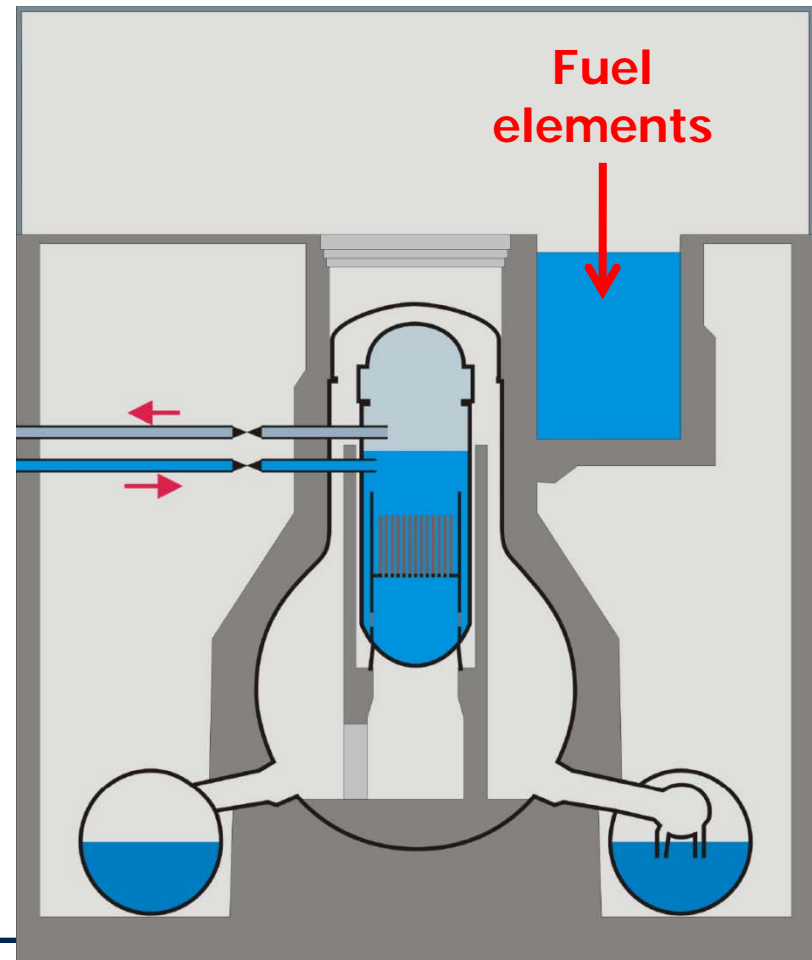
Accident progression

11.3.2011

Units 1, 2 and 3 in operation

Units 4, 5 and 6 closed down

Spent fuel pools in top of reactor buildings



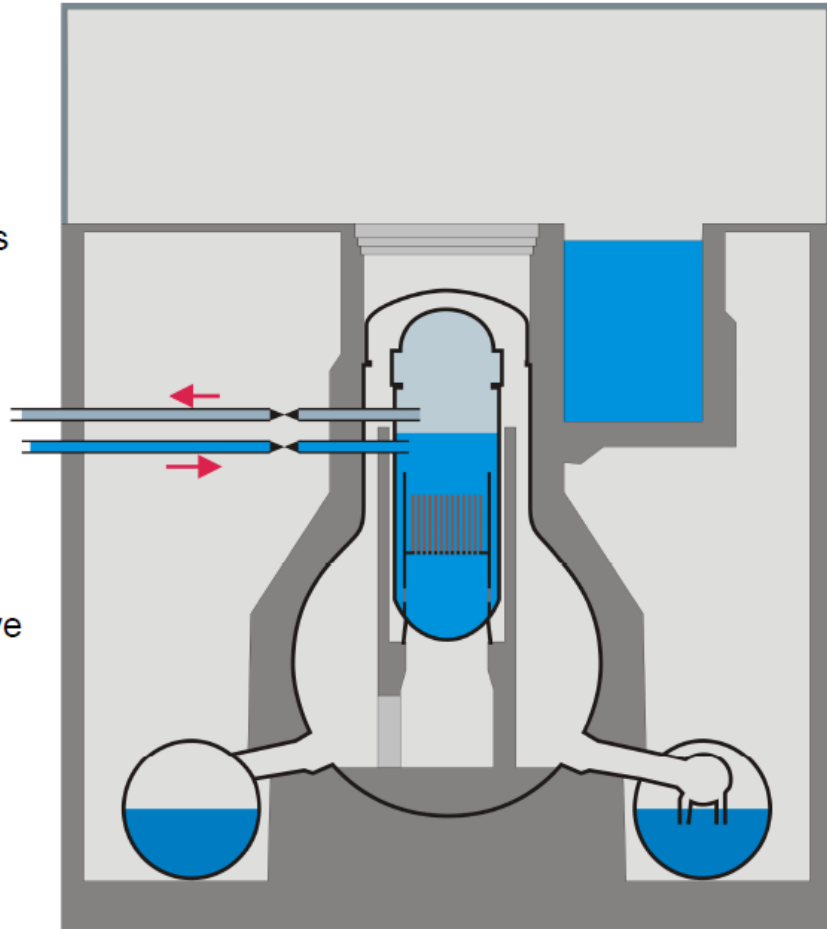
2. Accident Progression

► 11.3.2011 14:46 - Earthquake

- ◆ Magnitude 9
- ◆ Power grid in northern Japan fails
- ◆ Reactors itself are mainly undamaged

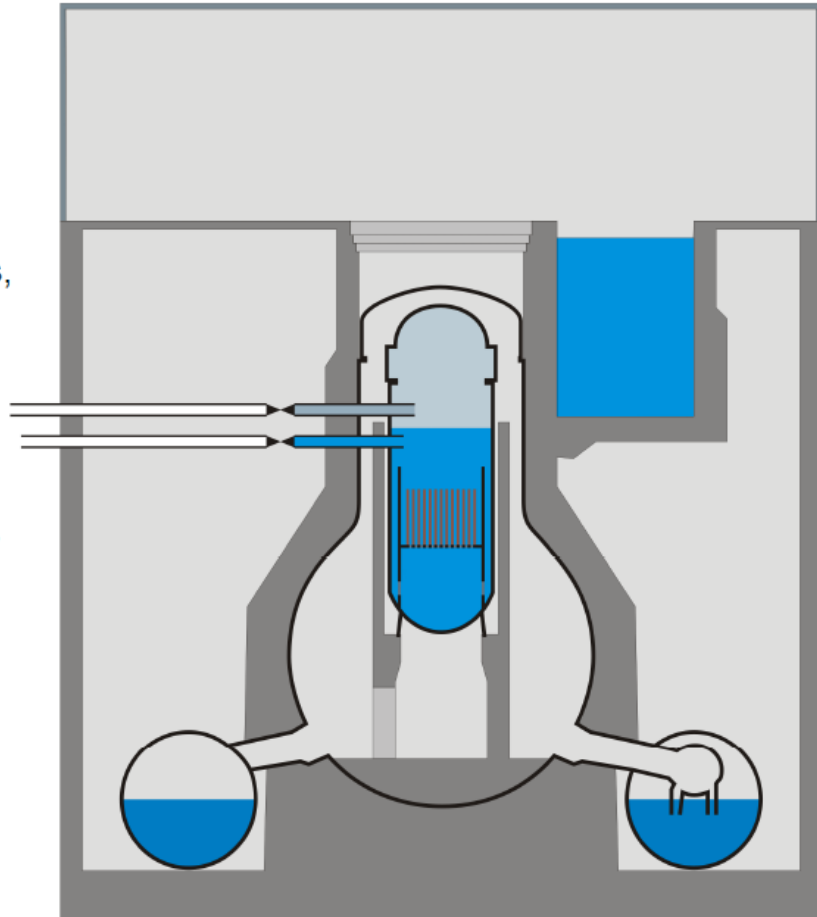
► Automatic SCRAM

- ◆ Power generation due to fission stopped
- ◆ Heat generation due to radioactive decay of fission products
 - After SCRAM ~6%
 - After 1 Day ~1%
 - After 5 Days ~0.5%



2. Accident Progression

- ▶ Containment Isolation
 - ◆ Closing of all non-safety related penetrations of the containment
 - ◆ Cuts off turbine building
 - ◆ If containment isolation succeeds, a large early release of fission products is highly unlikely
- ▶ Diesel generators start
 - ◆ Emergency core cooling systems are supplied
- ▶ Plant is in a stable state



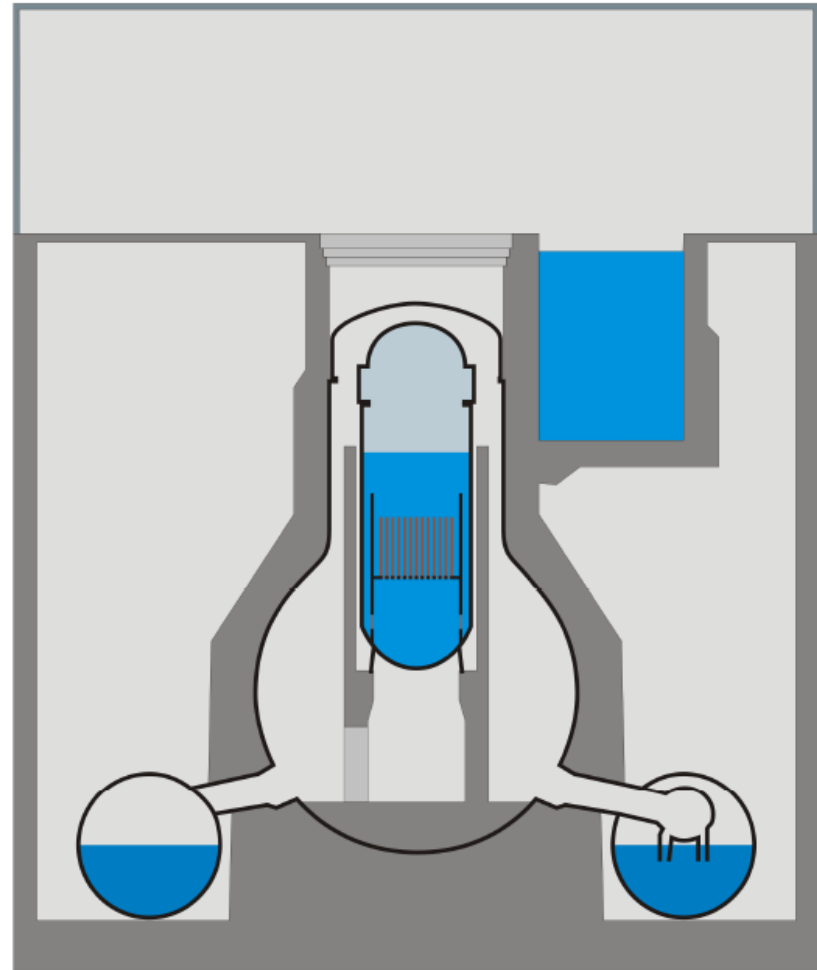
2. Accident Progression

▶ 11.3. 15:41 Tsunami hits the plant

- ◆ Plant design for tsunami height of up to 5.7m, protection 6.5m
- ◆ Actual tsunami height ~14m
- ◆ Flooding of
 - Diesel generators and/or
 - Essential service water building

▶ Station Blackout

- ◆ Common cause failure of the power supply
- ◆ Only batteries are available
- ◆ Loss of all emergency core cooling systems, only the steam driven containment isolation pump is available



2. Accident Progression

► Fukushima I Unit 1

◆ Isolation Condenser

- Steam enters heat exchanger
- Condensate drains back to reactor pressure vessel
- Secondary steam released from plant

◆ Need pumps for water supply

► Fukushima I Unit 2 and 3

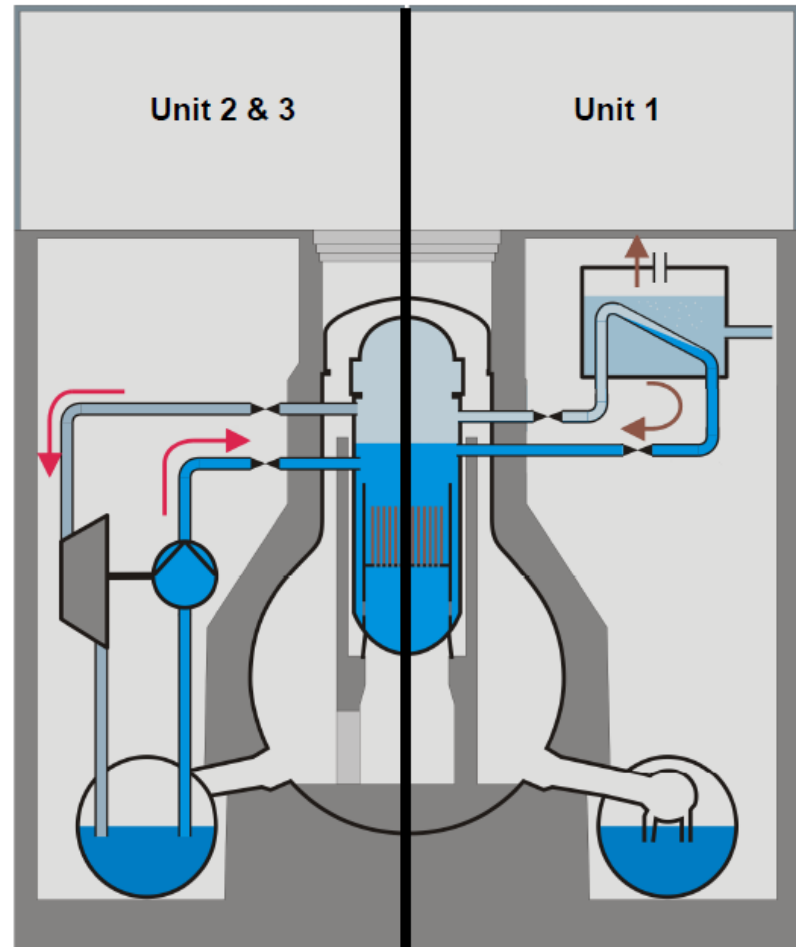
◆ Reactor Core Isolation Pump

- Steam from reactor drives turbine
- Turbine drives a pump, pumping water from the wet-well in the reactor
- Steam gets condensed in wet-well

◆ Necessary:

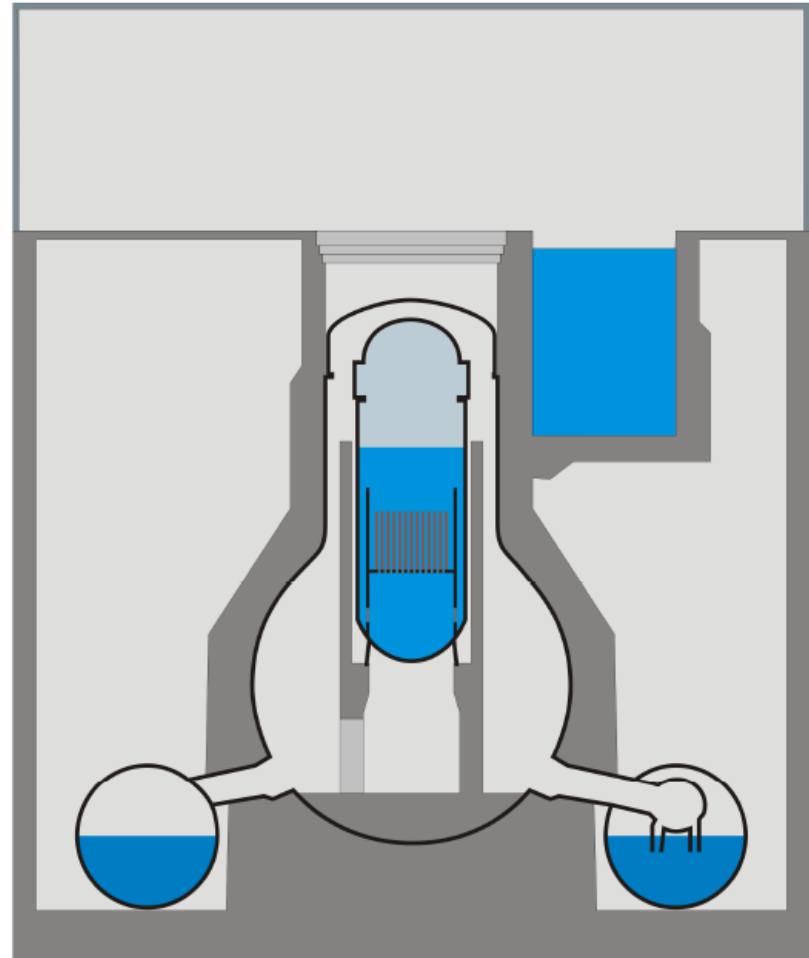
- Battery power
- Wet-well temperature < 100°C

◆ No heat removal from the buildings



2. Accident Progression

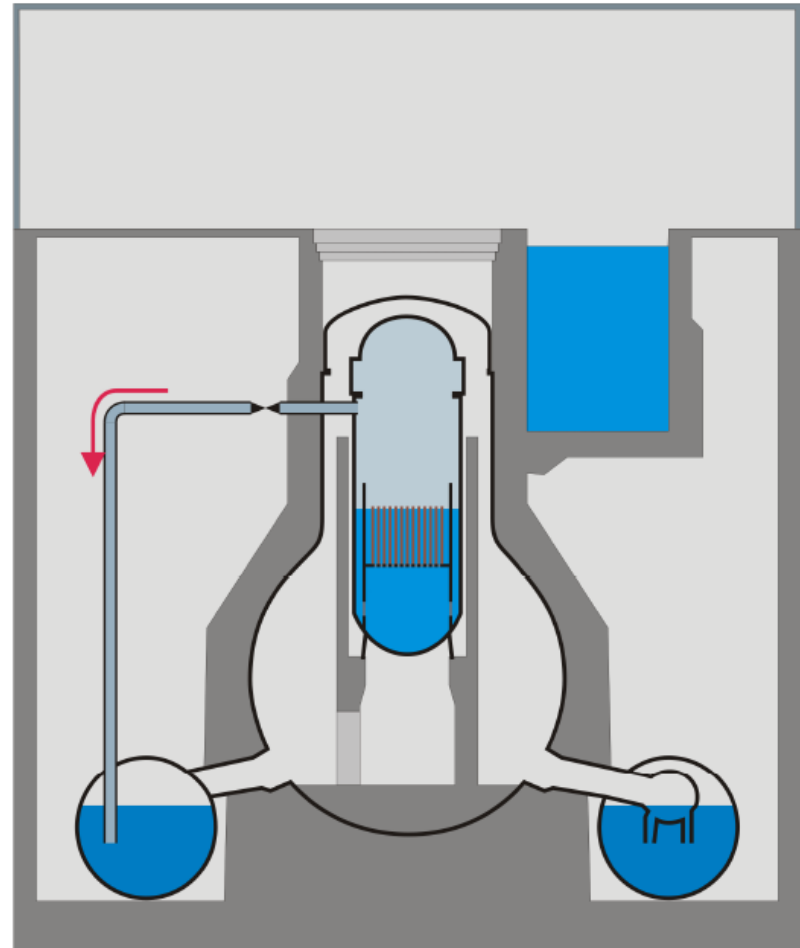
- ▶ 11.3. 16:36 in Unit 1
 - ◆ Isolation condenser stops
 - ◆ Pool empty?
- ▶ 13.3. 5:30 in Unit 3
 - ◆ Reactor Isolation pump stops
 - ◆ Batteries empty?
- ▶ 14.3. 13:25 in Unit 2
 - ◆ Reactor Isolation pump stops
 - ◆ Pump failure?
- ▶ Reactors of Units 1-3 are cut off from any kind of heat removal



2. Accident Progression

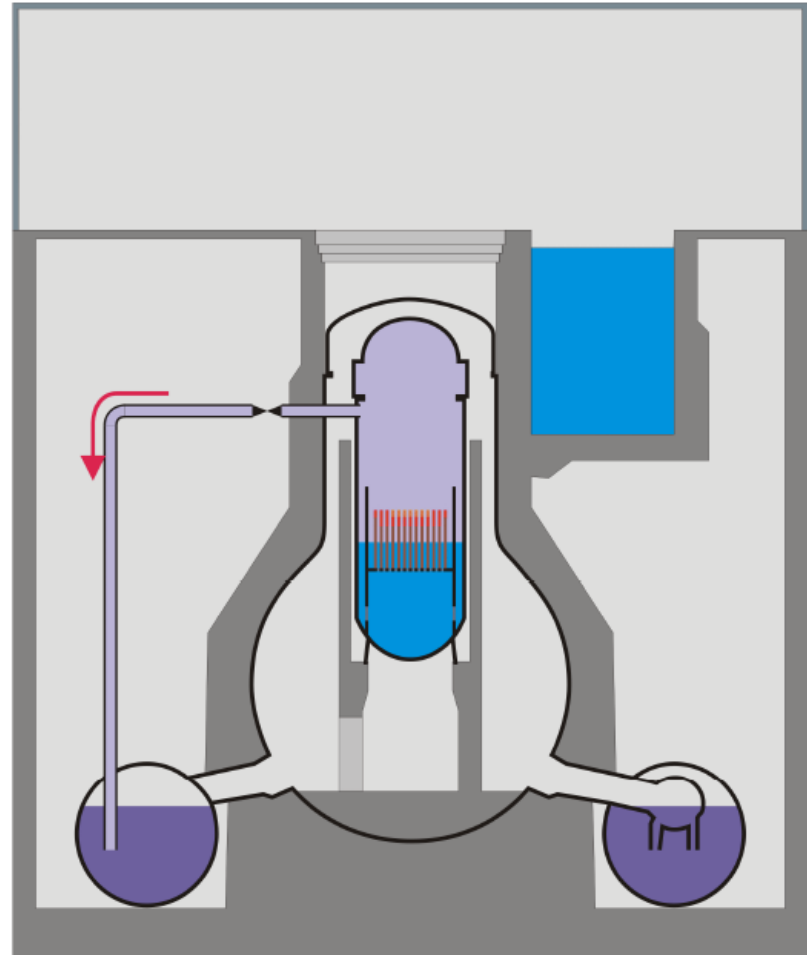


- ▶ Decay heat produces steam in reactor pressure vessel
 - ◆ Pressure rising
- ▶ Opening the steam relieve valves
 - ◆ Discharge steam into the wet-well
- ▶ Decreasing of the liquid level in the reactor pressure vessel



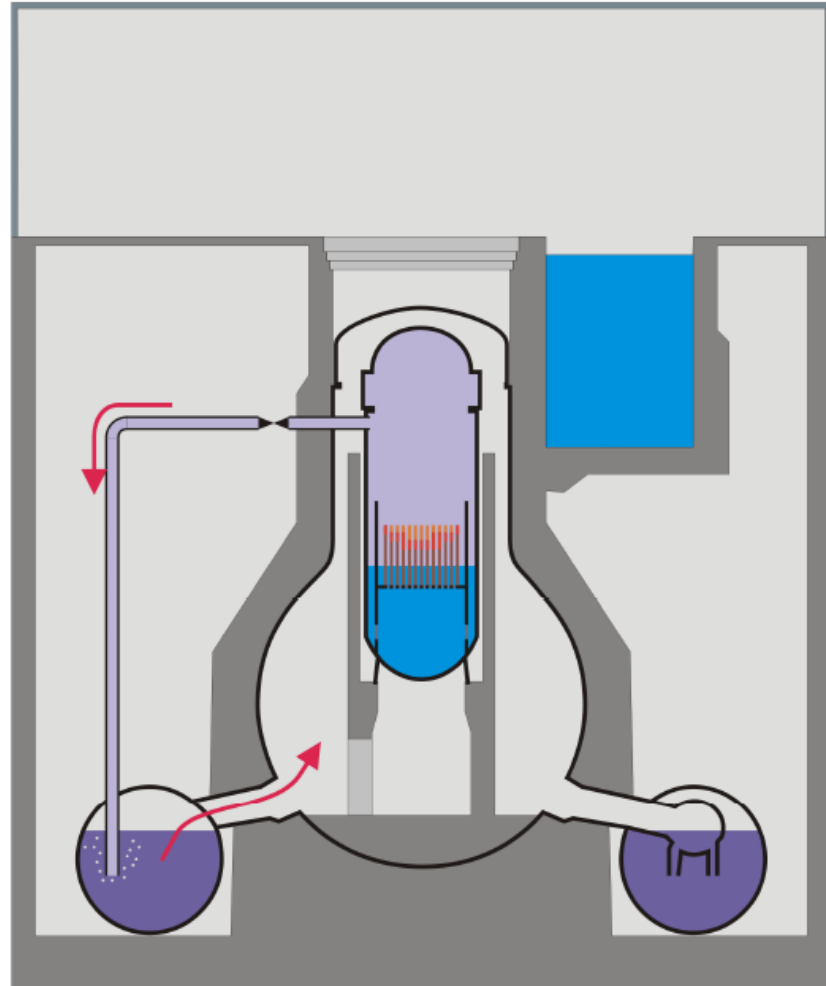
2. Accident Progression

- ▶ Measured, and here referenced liquid level is the collapsed level. The swell level is higher due to the steam bubbles in the liquid
- ▶ ~50% of the core exposed
 - ◆ Cladding temperatures rise, but still no significant core damage
- ▶ ~2/3 of the core exposed
 - ◆ Cladding temperature exceeds $\sim 900^{\circ}\text{C}$
 - ◆ Ballooning / Breaking of the cladding
 - ◆ Release of fission products from the fuel rod gaps



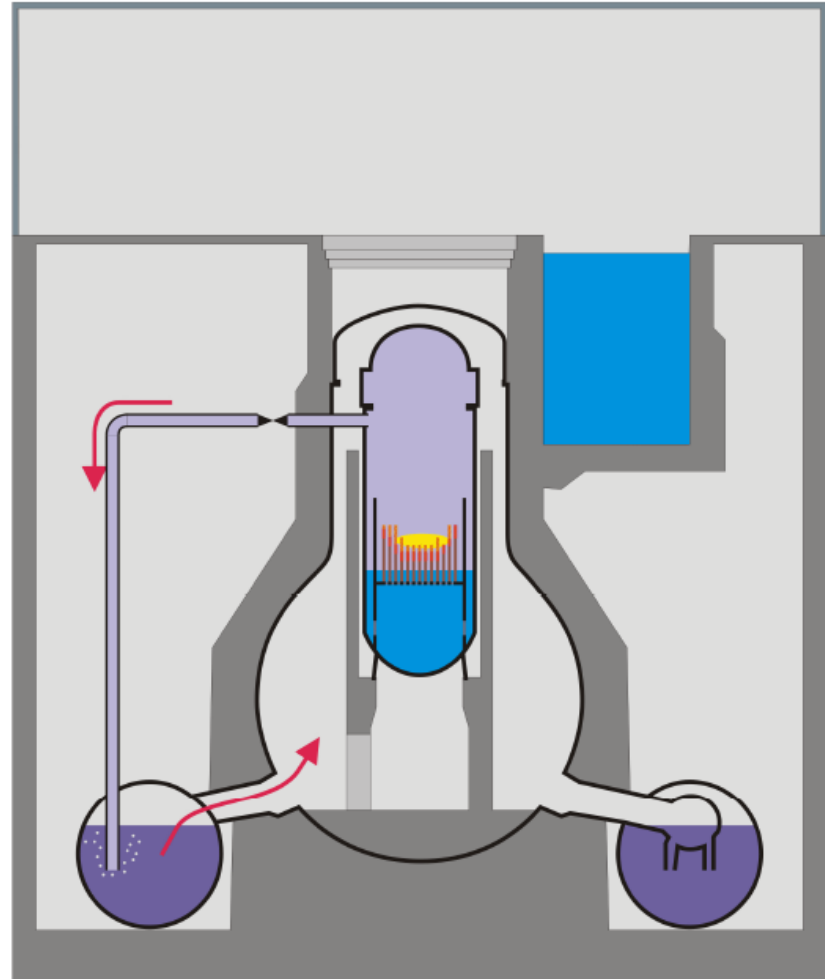
2. Accident Progression

- ▶ ~3/4 of the core exposed
 - ◆ Cladding exceeds ~1200°C
 - ◆ Zirconium water reaction starts under steam atmosphere
 - ◆ $\text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2$
 - ◆ Exothermal reaction heats the core additionally
 - ◆ Generation of hydrogen
 - Unit 1: 300-600kg
 - Unit 2/3: 300-1000kg
 - ◆ Hydrogen gets pushed via the wet-well, the wet-well vacuum breakers into the dry-well



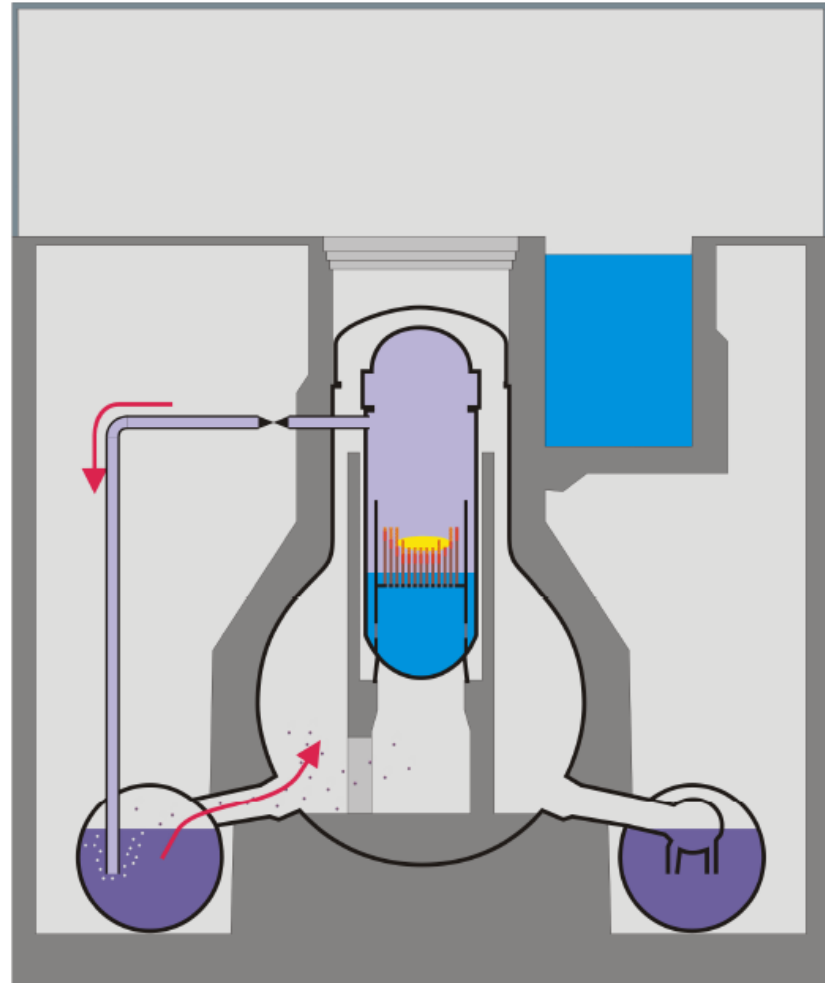
2. Accident Progression

- ▶ at ~1800°C [Unit 1,2,3]
 - ◆ Melting of the cladding
 - ◆ Melting of the steel structures
- ▶ at ~2500°C [Unit 1,2]
 - ◆ Breaking of the fuel rods
 - ◆ debris bed inside the core
- ▶ at ~2700°C [Unit 1]
 - ◆ Melting of Uranium-Zirconium eutectics
- ▶ Supply of seawater to the reactor pressure vessel stops the core melt in all 3 Units
 - ◆ Unit 1: 12.3. 20:20 (27h w/o water)
 - ◆ Unit 2: 14.3. 20:33 (7h w/o water)
 - ◆ Unit 3: 13.3. 9:38 (7h w/o water)



2. Accident Progression

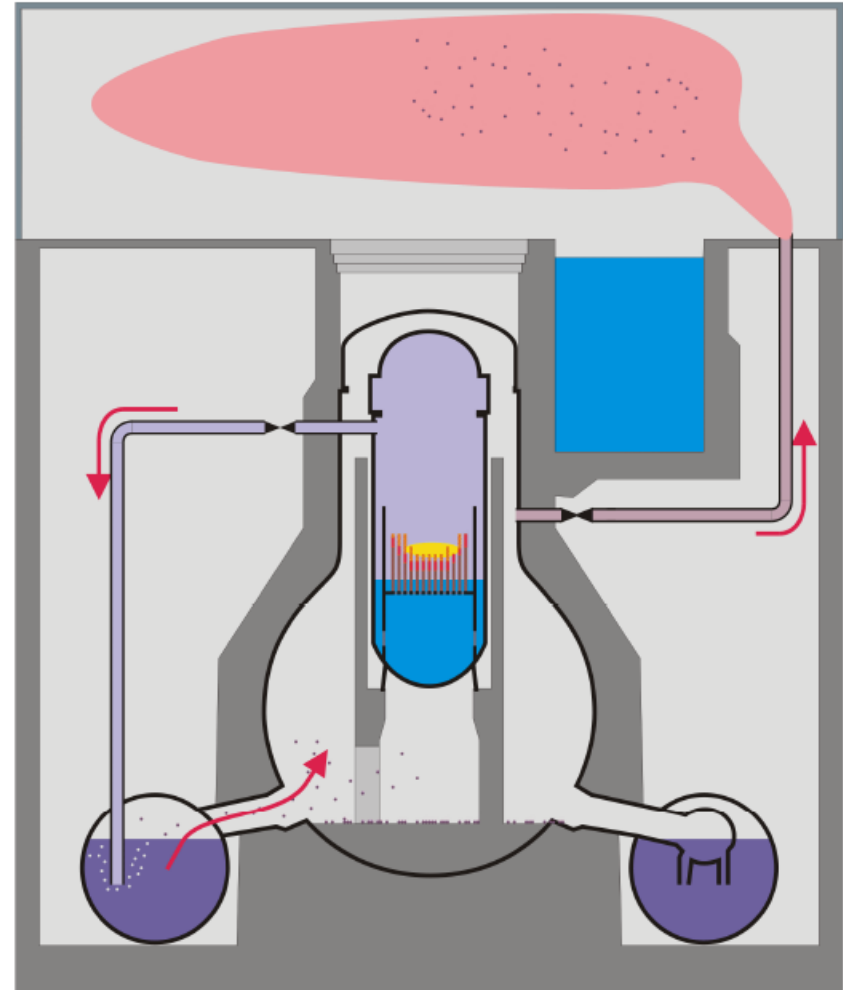
- ▶ Release of fission products during melt down
 - ◆ Xenon, Cesium, Iodine,...
 - ◆ Uranium/Plutonium remain in the core
 - ◆ A part of the fission products condensate to airborne aerosols
- ▶ Discharge through valves into water of the condensation chamber
 - ◆ Pool scrubbing binds a fraction of aerosols in the water
- ▶ Xenon and remaining aerosols enter the dry-well
 - ◆ Deposition of aerosols on surfaces decontaminates air



2. Accident Progression

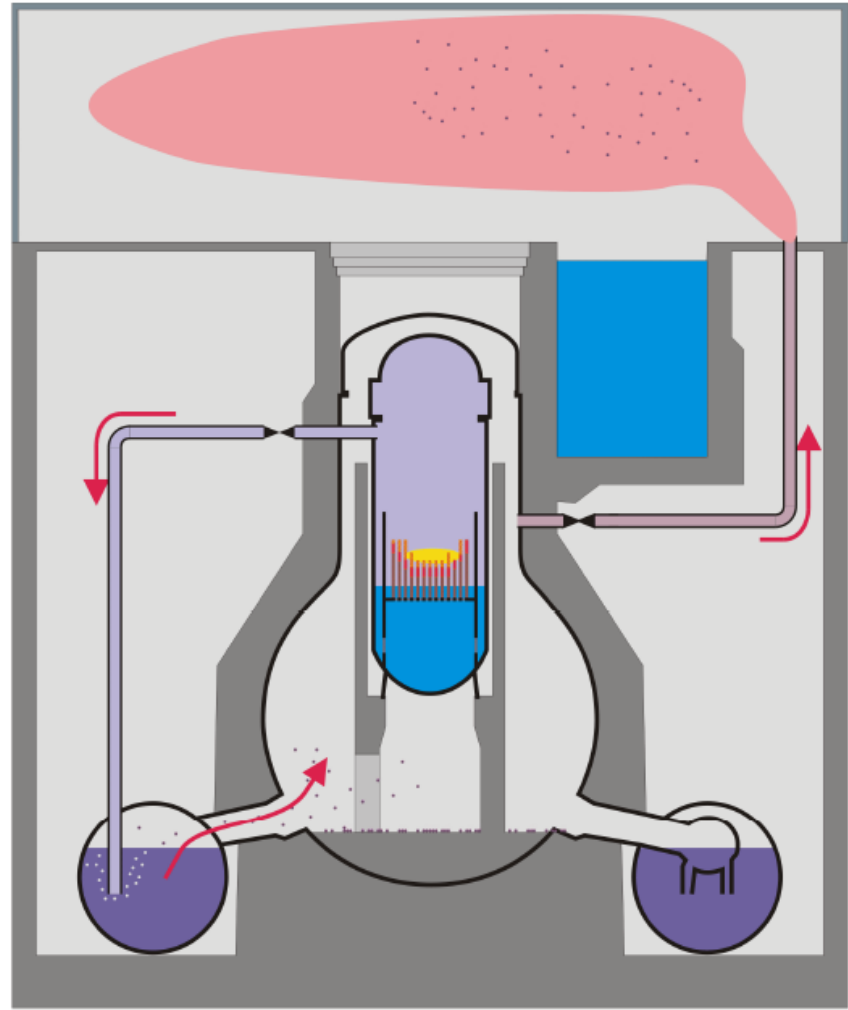


- ▶ Containment
 - ◆ Last barrier between fission products and environment
 - ◆ Wall thickness ~3cm
 - ◆ Design pressure 4-5bar
- ▶ Pressure reached up to 8 bars
 - ◆ Normal inert gas filling (Nitrogen)
 - ◆ Hydrogen from core oxidation
 - ◆ Boiling in the condensation chamber
- ▶ Depressurization of the containment
 - ◆ Unit 1: 12.3. 4:00
 - ◆ Unit 2: 13.3 00:00
 - ◆ Unit 3: 13.3. 8:41



2. Accident Progression

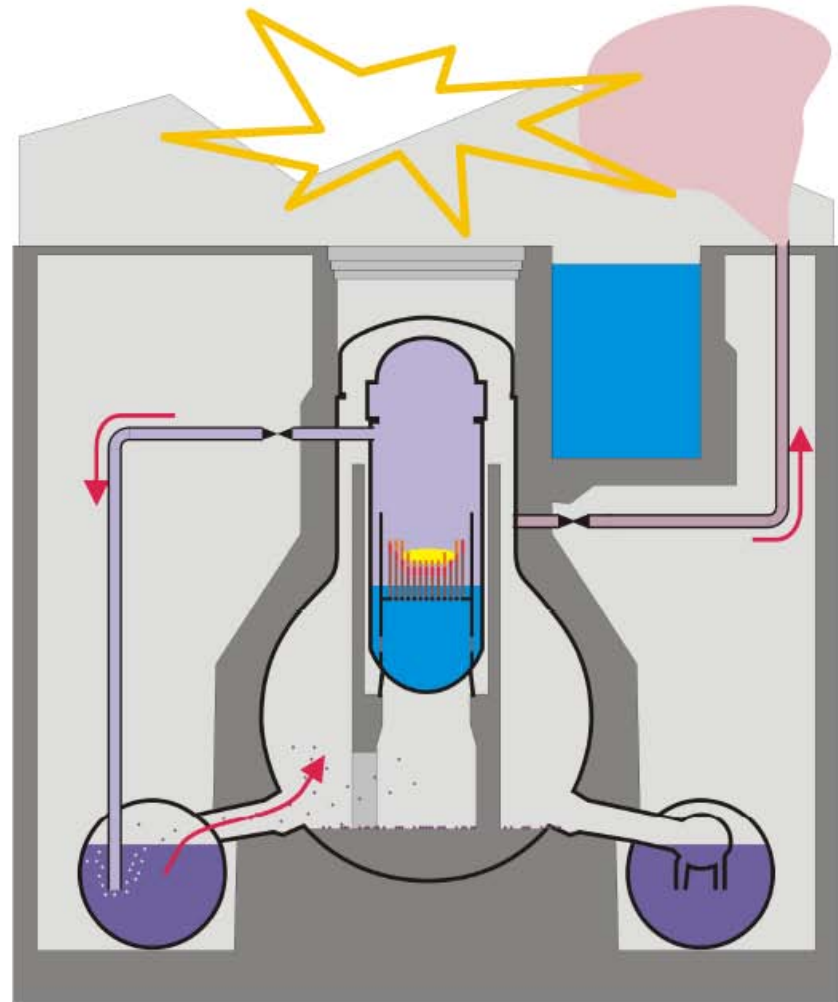
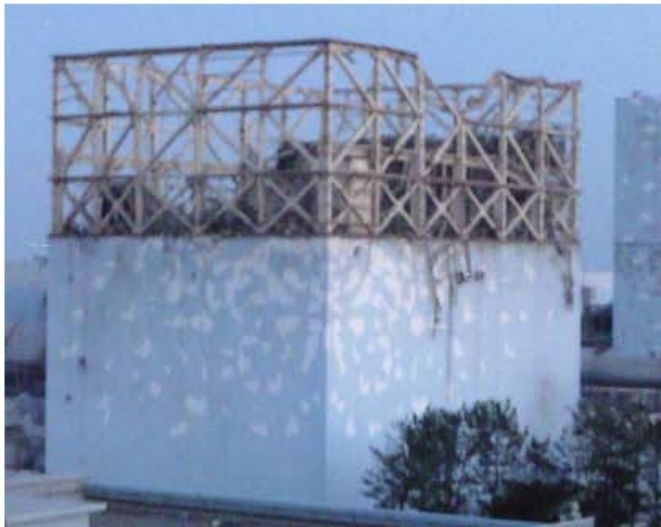
- ▶ Positive and negative aspects of depressurizing the containment
 - ◆ Removes energy from the containment (the only way left)
 - ◆ Reducing the pressure to ~4 bar
 - ◆ Release of small amounts of aerosols (Iodine, Cesium ~0.1%)
 - ◆ Release of all noble gases
 - ◆ Release of hydrogen
- ▶ Gas is released into the reactor service floor



2. Accident Progression

► Unit 1 and 3

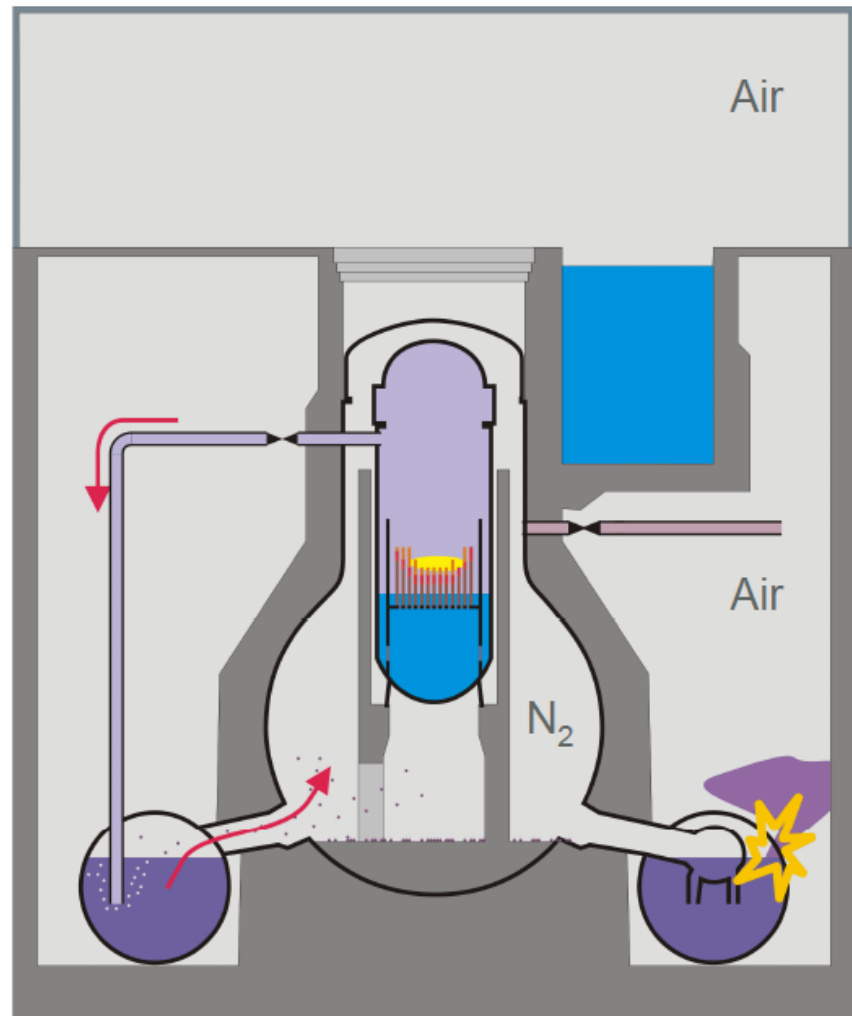
- ◆ Hydrogen explosion inside the reactor service floor
- ◆ Destruction of the steel-frame construction
- ◆ Reinforced concrete reactor building seems undamaged



2. Accident Progression

► Unit 2

- ◆ Probably damage of the condensation chamber following a pressure increase in the reactor pressure vessel and containment (highly contaminated water)
- ◆ Uncontrolled release of gas and **fission products** from the containment
- ◆ Temporal evacuation of the plant
- ◆ High local dose rates on the plant site

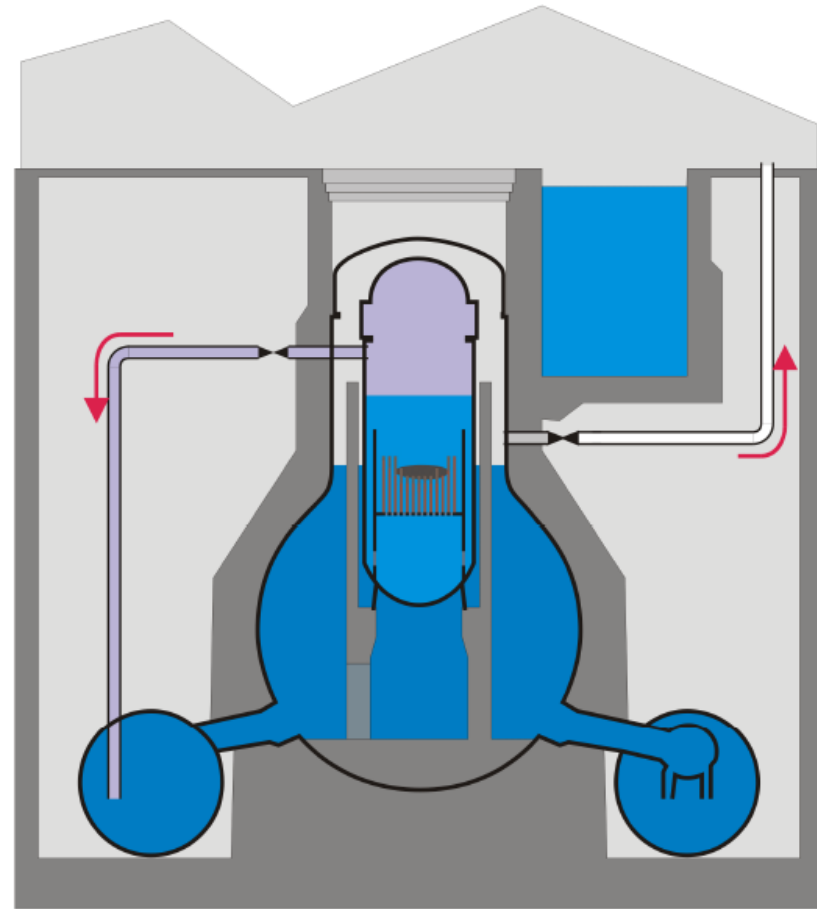


2. Accident Progression



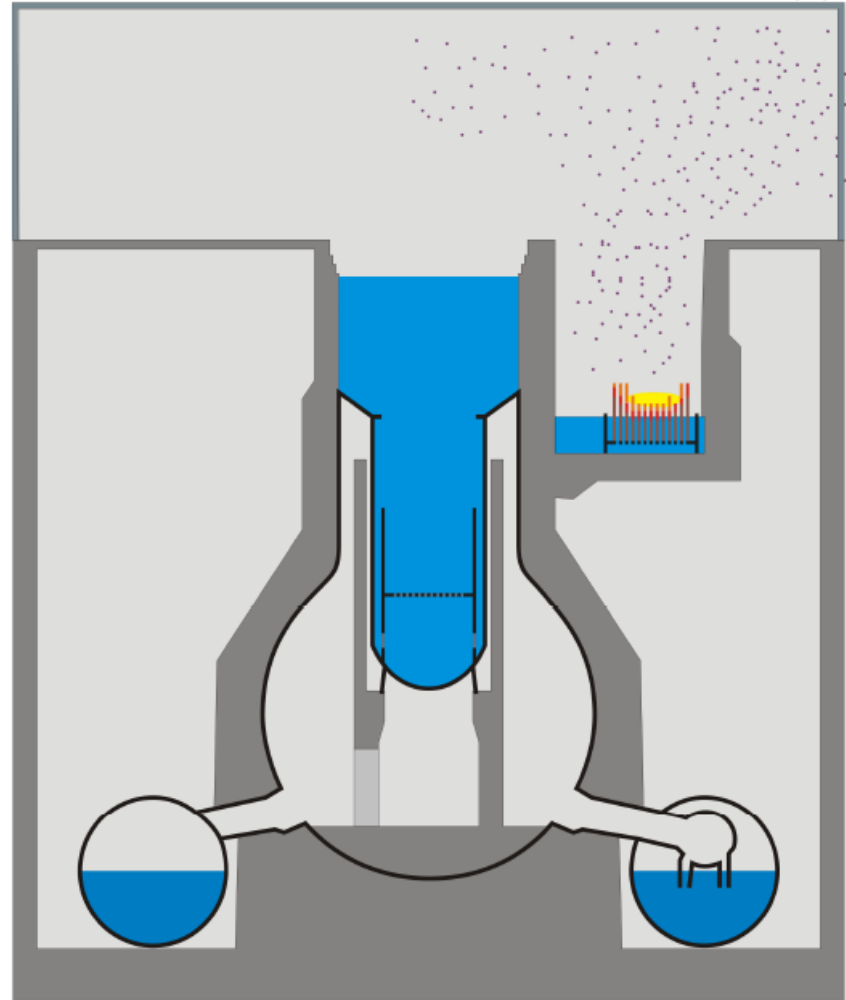
► Current status of the reactors

- ◆ Core damage in Unit 1, 2, 3
- ◆ Building damages of Unit 1-4
- ◆ Reactor pressure vessels feeding with seawater in all units by mobile pumps
- ◆ Containment in Unit 1 flooded



3. Spent Fuel Pools

- ▶ Spent fuel stored in pool on reactor service floor
 - ◆ Due to maintenance in Unit 4 entire core stored in fuel pool
 - ◆ Dry-out of the pools
 - Unit 4: in 10 days
 - Unit 1-3,5,6 in few weeks
 - ◆ **Leakage of the pools due to Earthquake?**
- ▶ Consequences
 - ◆ Fuel melt in direct contact to the atmosphere
 - ◆ Nearly no retention of fission products
 - ◆ Large release possible



4. Current Status

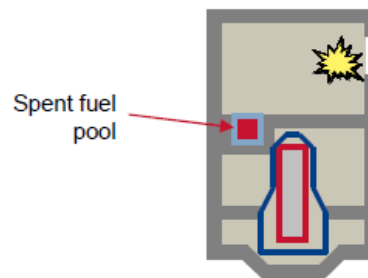
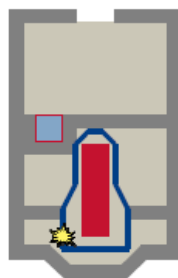
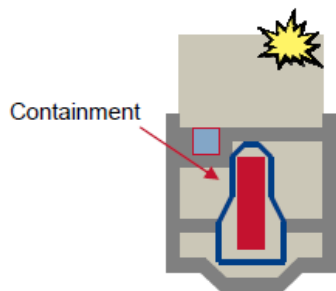


Units 1 and 3

Unit 2

Unit 4

Units 5 and 6



Units in operation at the time of the earthquake

Units shutdown at the time of the earthquake

- ▶ Containment and RPV¹ intact
- ▶ Partial core meltdown
- ▶ Reactor service floor damaged
- ▶ Situation stabilised (ongoing cooling by spraying from outside)
- ▶ Unit 1 and 3 are connected to the external grid

- ▶ Containment slightly damaged
- ▶ Partial core meltdown
- ▶ Reactor service floor damaged
- ▶ RPV intact
- ▶ Ongoing cooling to avoid leakage of RPV
- ▶ Feed of seawater in the spent fuel pool started on March, 20th 2011

- ▶ Unit 2 is connected to the external grid

- ▶ Core completely in the spent fuel pool
- ▶ Reactor service floor damaged
- ▶ Status of the water level in the spent fuel pool unknown
- ▶ Cooling of the spent fuel pool difficult
- ▶ Preparation for reconnection to the external grid

- ▶ Core partially in the spent fuel pool
- ▶ Temperature in the spent fuel pool stable at 30°C resp. 35 °C
- ▶ Status of the reactor "cold, subcritical"
- ▶ Open a vent hole on the rooftop for avoiding hydrogen explosion

¹ Reactor pressure vessel
Note: All timing information in GMT+1



3-4. Chronology of Unit 1 after the earthquake

● **Unit 1**

- 11th ● Under operation, Automatic shutdown by the earthquake
 - Loss of A/C power
 - Loss of water injection function
- 12th ● Unusual increase of PCV pressure
 - Started to vent
 - Sound of explosion
 - Started of injection of seawater and borated water to the core
- 22nd ● Rise of reactor temperature (383°C) → Drop (26th 05:00 144.3°C)
- 23rd ● Water supply line in addition to the Fire Extinguish line. Switched to water supply line only.(Flow rate: 7m³/h)
- 24th ● Lighting in the Central Control Room was recovered.
- 25th ● Started fresh water injection
- 29th ● Switched to the water injection to the core using a temporary motor operated pump.
- 31st ● White smoke was confirmed to generate continuously
 - Freshwater is being injected into the RPV

14

APPENDIKS A: INES, den internationale skala for uheld på nukleare anlæg

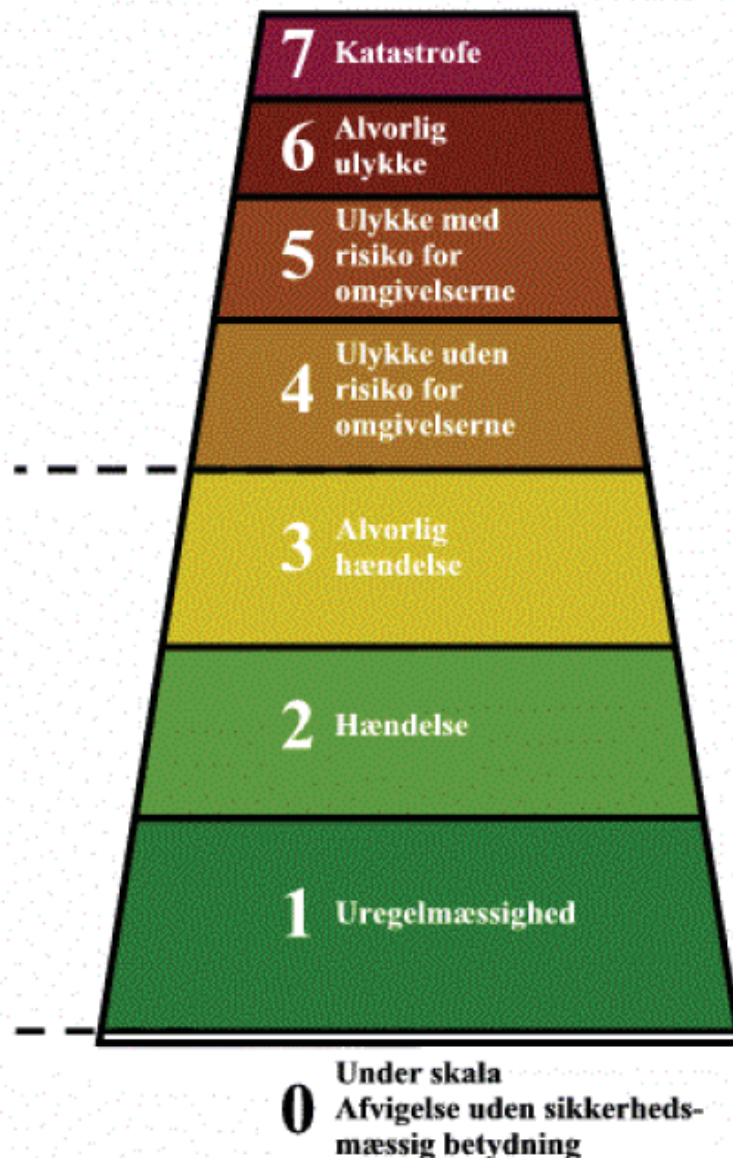
På foranledning af IAEA og OECD/NEA blev der i 1990 udviklet en skala til angivelse af den sikkerhedsmæssige betydning af uheld på nukleare anlæg og uheld ved transport af radioaktivt materiale.

Skalaen betegnes INES, International Nuclear Event Scale, og omfatter otte uheldsklasser, fra klasse 0 til 7 (se figuren). Hændelser, der ikke har nogen sikkerhedsmæssig betydning, placeres i klasse 0, mens alvorlige ulykker med udslip af store mængder radioaktivt materiale hører til klasse 7.

Uheldsklassen bestemmes ud fra tre kriterier:

- Påvirkning af omgivelserne
- Påvirkning af anlægget
- Degradering af dybdeforsvaret (anlæggets sikkerhedssystem).

Uheld med påvirkning af omgivelserne ved udslip af radioaktivt materiale er det mest alvorlige kriterium og dækker klasse 3 til 7. Uheld, hvor der udelukkende sker en



Accident progression

11.3.2011 KI. 16:36

Loss of cooling in unit 1

13.3.2011 KI. 5:10

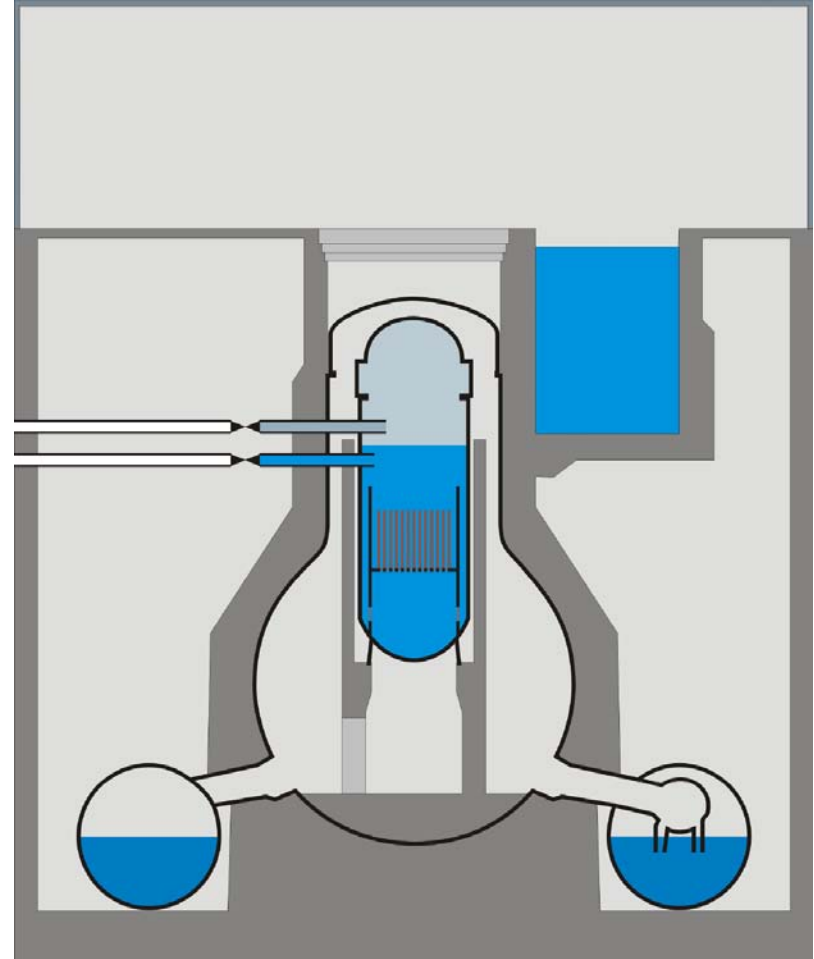
Loss of cooling in unit 3

14.3.2011 KI. 13:25

Loss of cooling in unit 2

12.3 Evacuation, 20 km zone

**Power plant unstable
INES level 4**



Accident progression

12-13.3.2011

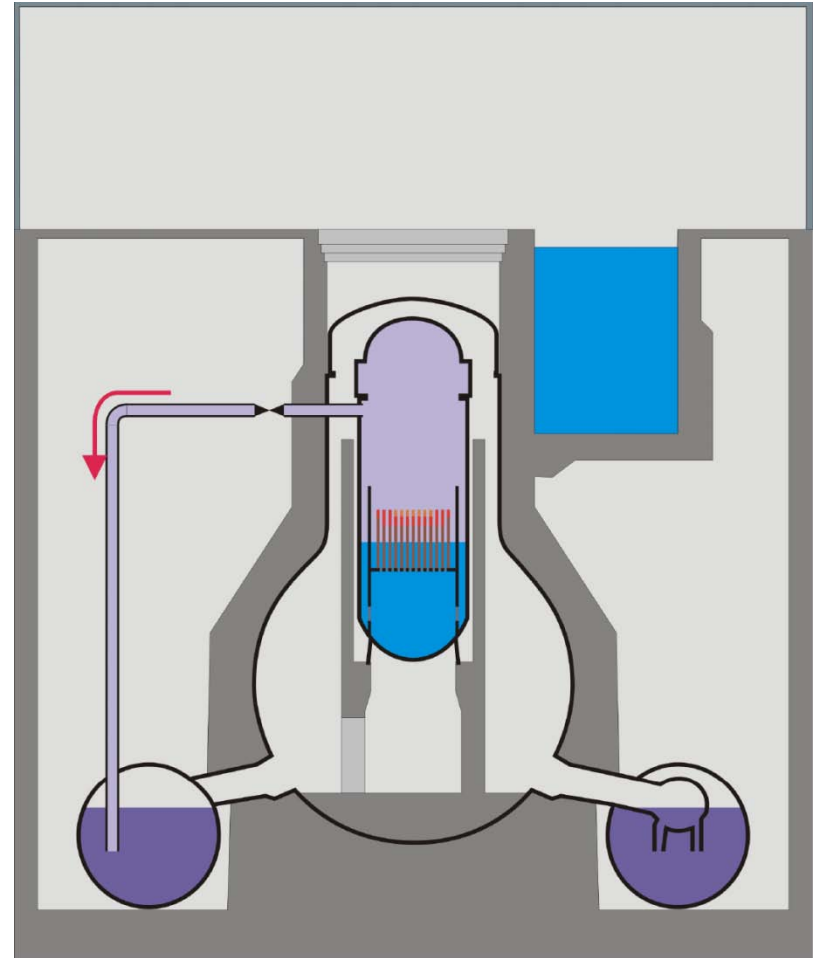
Temperature and pressure raising
Water level decreasing
Pressure release of RPV

Start of melt down

900 °C Release of radioactivity
1200 °C Hydrogen production
1800 °C Fuel cladding melts
2700 °C Fuel (U-Zr) melts

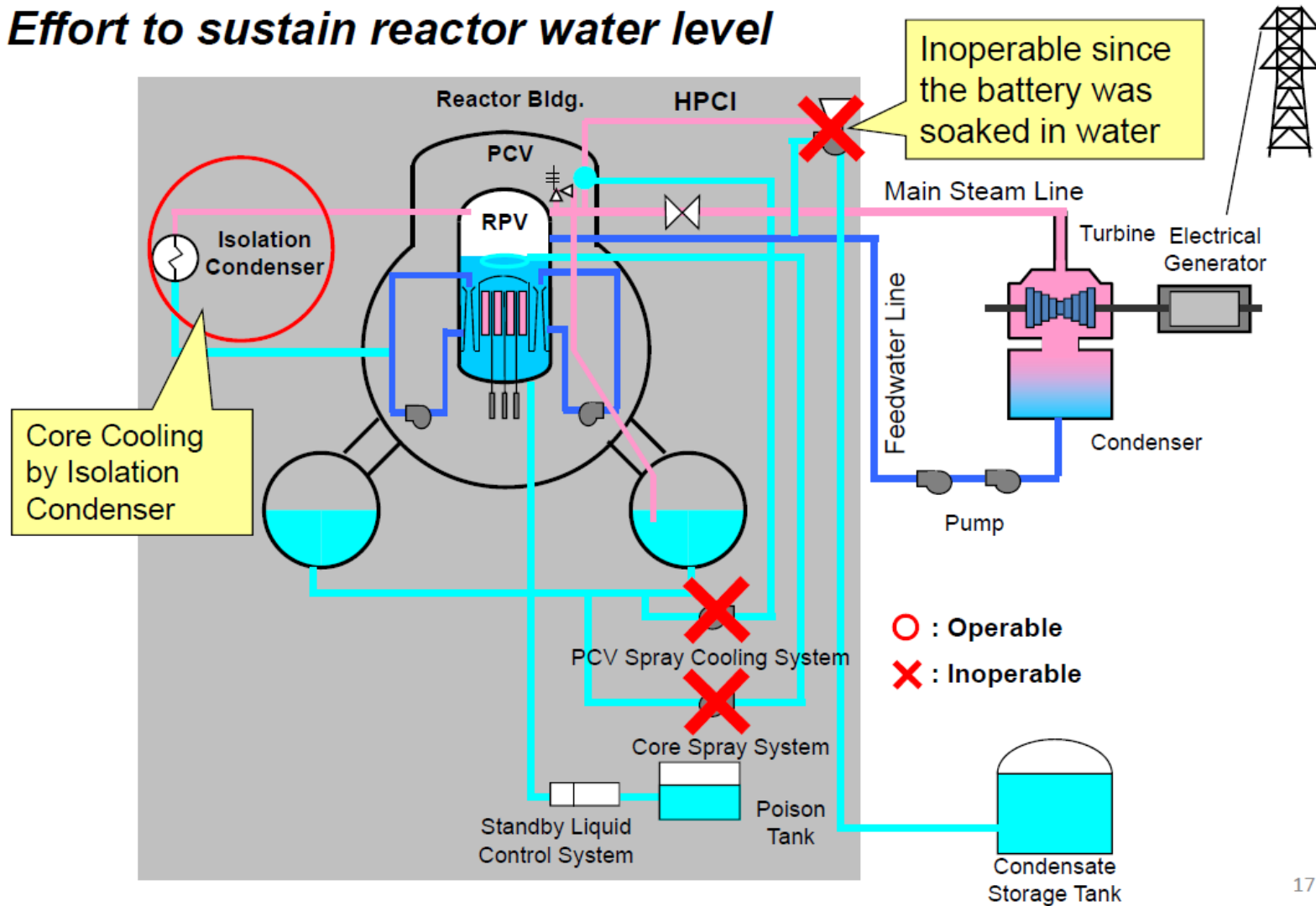
Reactor containment intact

Power plant very unstable
INES level 5



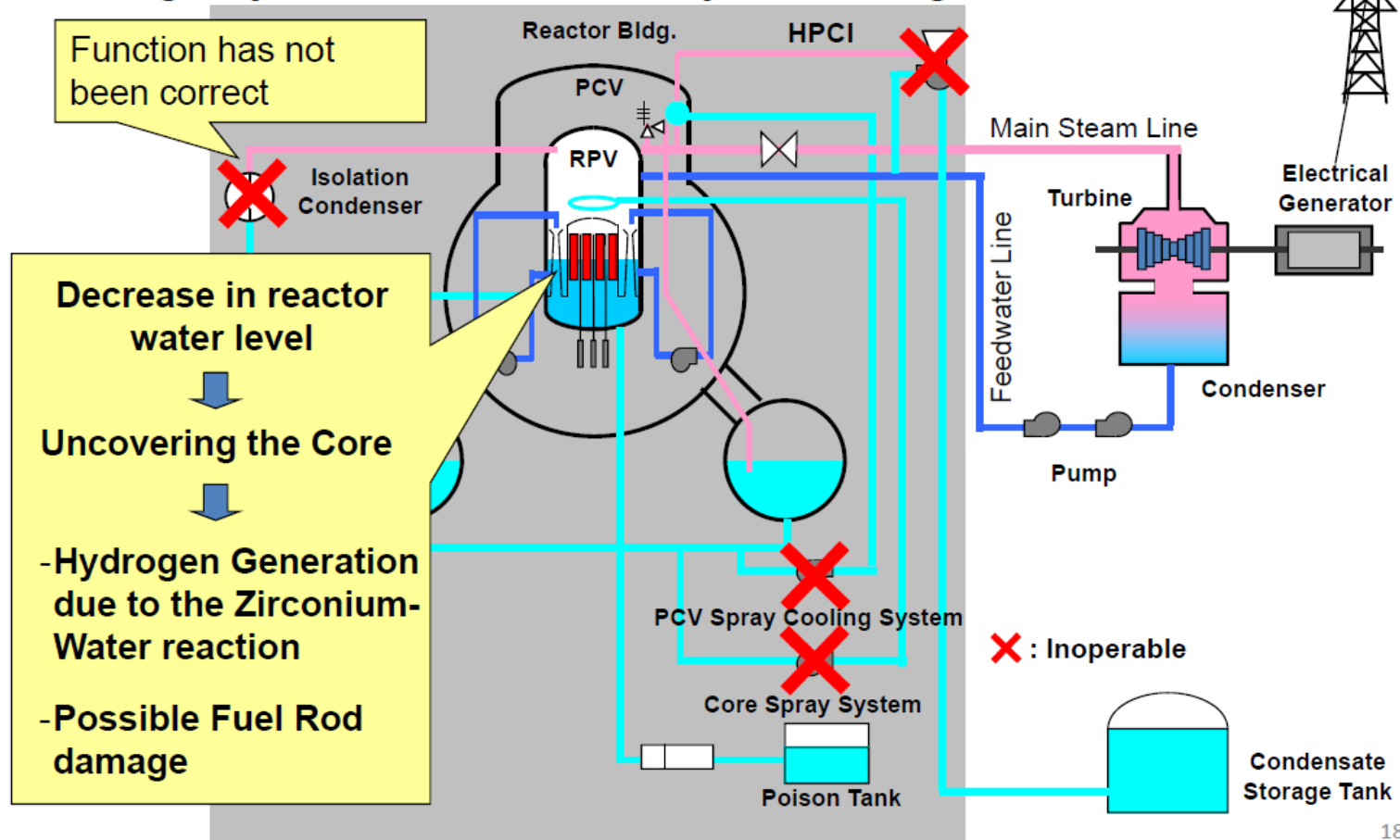
3-7. Major event progression at Unit 1 (1/4)

Effort to sustain reactor water level



3-7. Major event progression at Unit 1 (2/4)

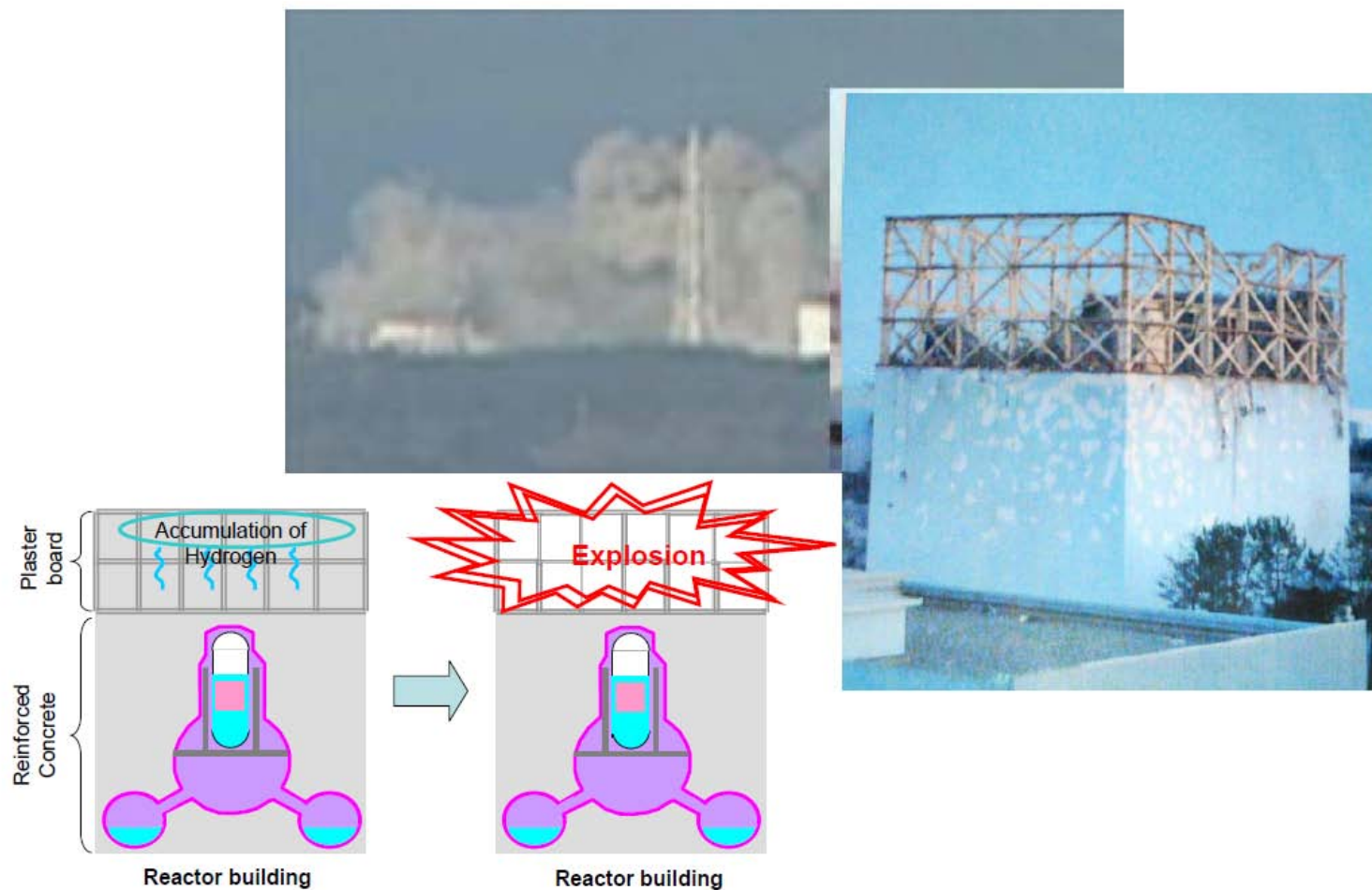
Decrease in reactor water level due to loss of cooling capability of emergency condenser, followed by uncovering the core



18

3-7. Major event progression at Unit 1 (3/4)

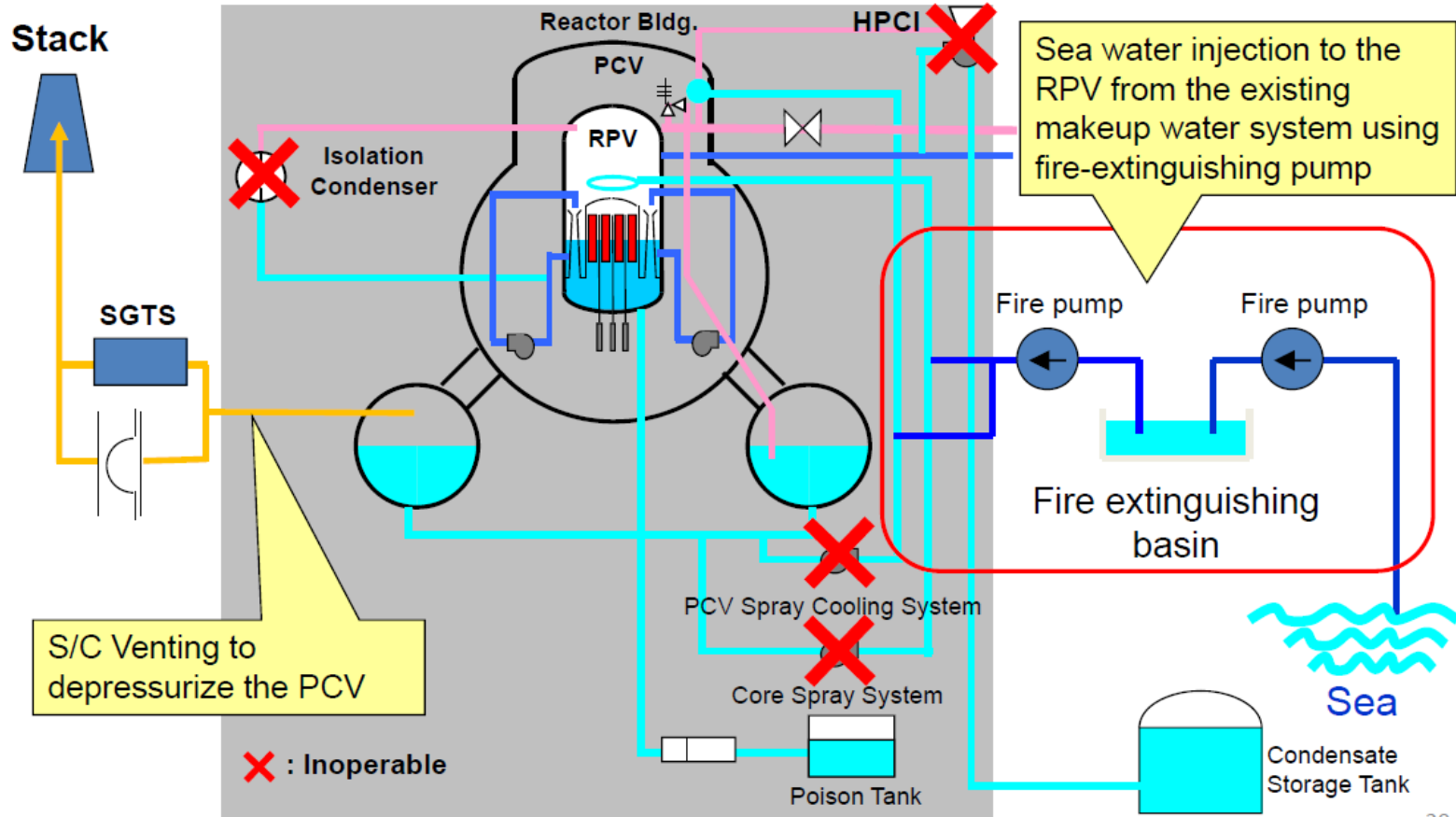
Hydrogen explosion in the operation floor



1

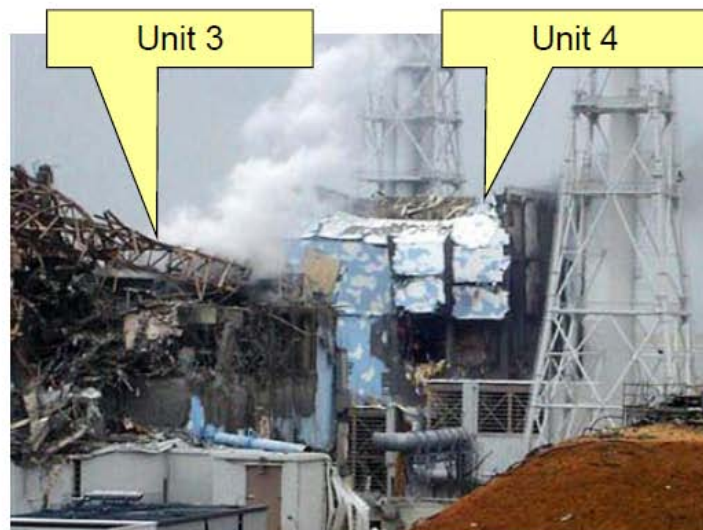
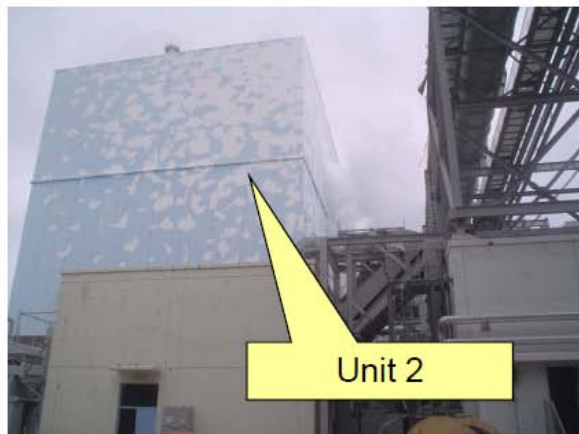
3-7. Major event progression at Unit 1 (4/4)

- **Sea water injection using fire water pump**
- **S/C Venting to depressurize the PCV**



20

3-8. Accident Progression at Unit 2 through 4 reactors

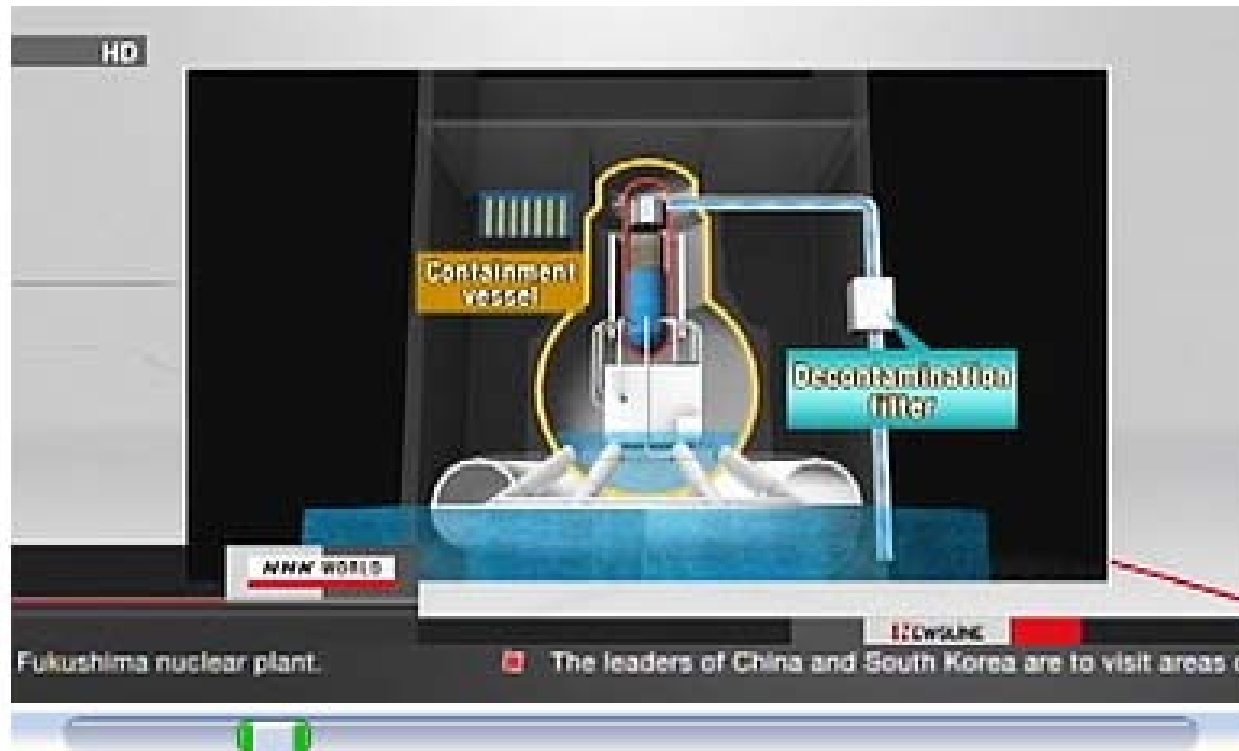


21

Melted fuel in unit 1



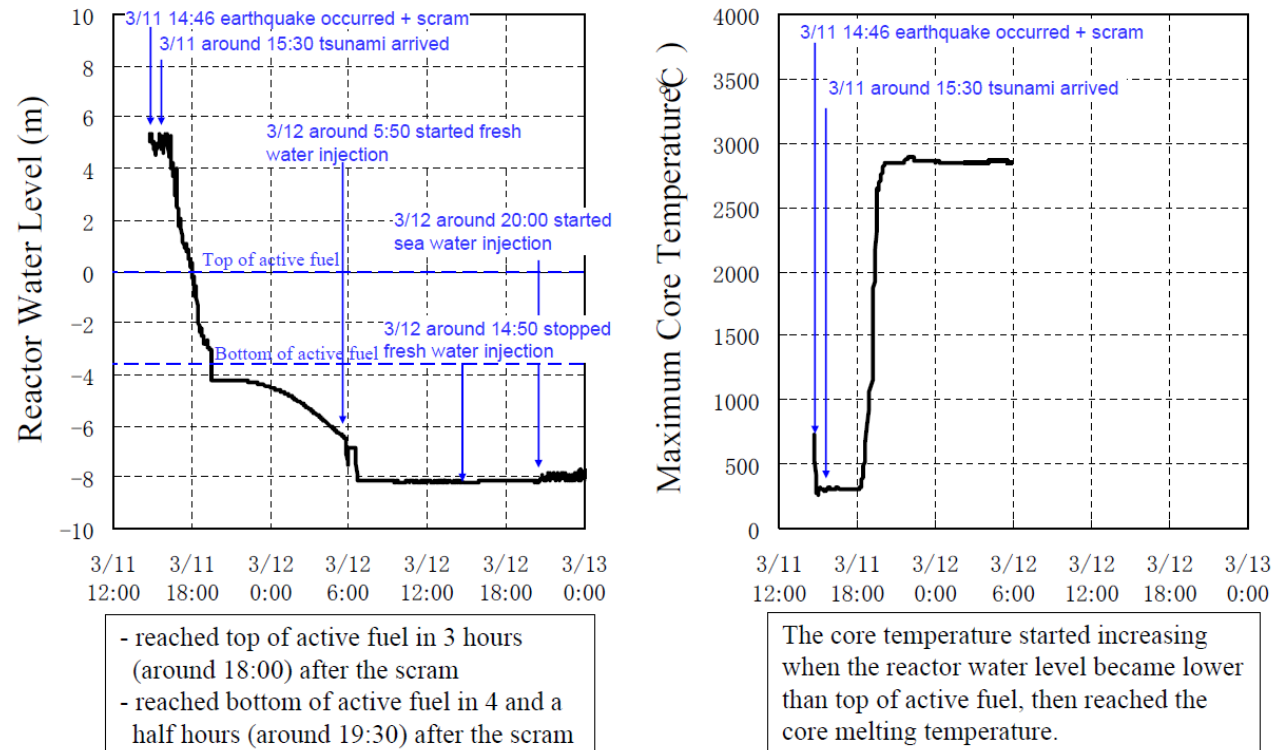
Recirculation, cooling and filtering of water from the bottom of containment



Simulation

Unit 1: Reactor Water Level, Maximum Core Temperature (Analysis Result)

Key assumption: IC lost its function after the tsunami arrived at around 15:30



Time and operations described herein might be revised according to the accident investigation in the future.

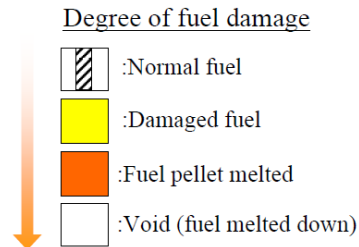


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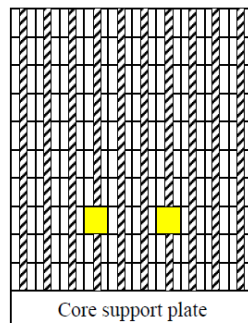
2

Core melt progressing unit 1

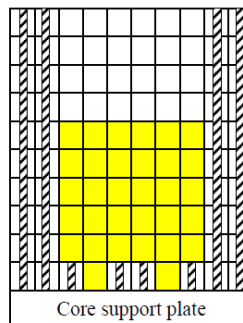
Unit 1: Transition of Core Status (analysis result)



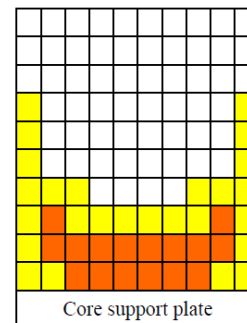
- Melting starts from the central part of the core.
- In 16 hours after scram (around March 12th 6:50), most part of the core fell down to the RPV bottom.
- Although RPV is damaged in this provisional analysis, the actual damage of RPV is considered to be limited according to the temperatures presently measured around the RPV.



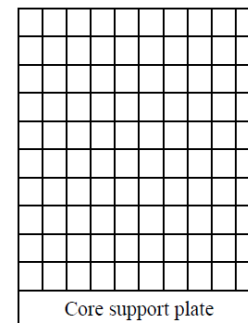
4.8 hours after scram
(around March 11th 19:30)



5.1 hours after scram
(around March 11th 19:50)



15.1 hours after scram
(around March 12th 6:00)



16.0 hours after scram
(around March 12th 6:50)

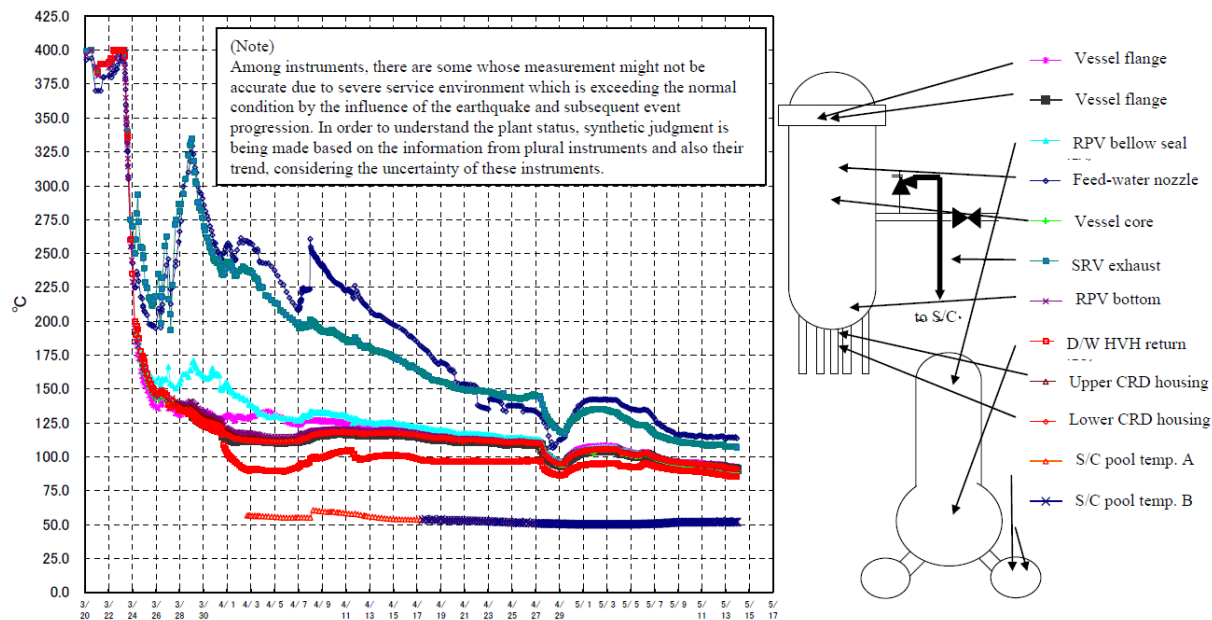


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3

Measured RPV temperatures

Unit 1: Temperatures around RPV (actual measurement value)



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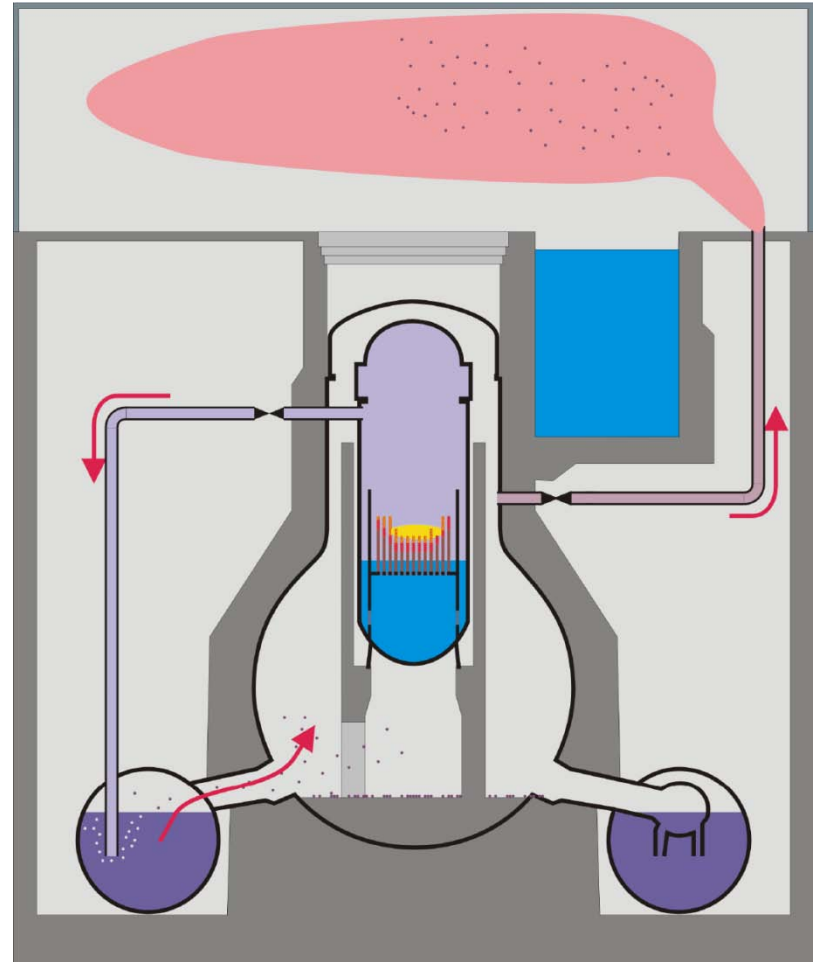
5

Units 1, 3

12 - 14.3.2011

Radioactive steam in reactor building
Hydrogen in reactor building

Power plant very unstable
INES level 5



Fukushima NPP after the accident



Reactor 2-4



Reactor 4





Units 1, 3

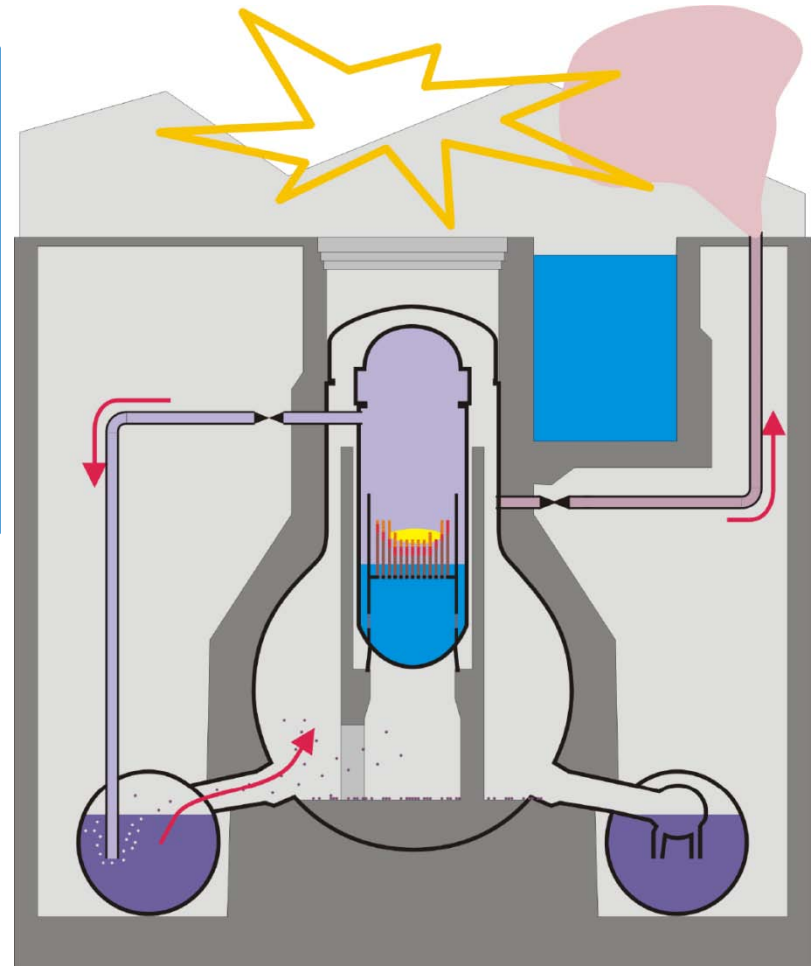
12 - 14.3.2011

Hydrogen explosions in units 1, 3

Release of noble gases

Small release of aerosols – Cs, I

Accident – level 5?



3-9. Chronology of Unit 2 after the earthquake (1/2)

● **Unit 2**

- 11th ● Under operation, Automatic shutdown by the earthquake
 - Loss of A/C power
 - Loss of water injection function
- 14th ● Loss of water cooling function
 - Unusual increase in PCV pressure
- 15th ● Sound of explosion
 - Possible damage of the suppression chamber
- 20th ● Injection of about 40 tons of seawater into SFP through fire extinguishing system.
 - Injection of seawater to the Spent Fuel Pool (SFP)
- 21st ● White smoke generated
- 22nd ● Injection of seawater to the Spent Fuel Pool (SFP)
- 25th ● Injection of seawater to SFP

3-9. Chronology of Unit 2 after the earthquake (2/2)

● *Unit 2(Continued)*

- 26th ● Lighting in the Central Control Room was recovered
- 27th ● Switched to the water injection to the core using a temporary motor-driven pump.
- 29th ● The Seawater injection to the Spent Fuel Pool using the Fire Pump Truck was switched to the fresh water injection using the temporary motor-driven pump
● In order to prepare for transferring the stagnant water on the basement floor of turbine building to the Condenser, the water in the Condensate Storage Tank is being transferred to the Surge Tank of Suppression Pool Water.
- 30th ● The injection pump was switched to the Fire Pump Truck. However, because cracks were confirmed in the hose (12:47 and 13:10 March 30th), the injection was suspended. The injection of fresh water resumed at 19:05 March 30th.
- 31st ● White smoke was confirmed to generate continuously.
● Fresh water is being injected to the spent fuel pool and the RPV

23

Unit 2

15.3.2011

Explosion in bottom of unit 2
(condensation chamber)

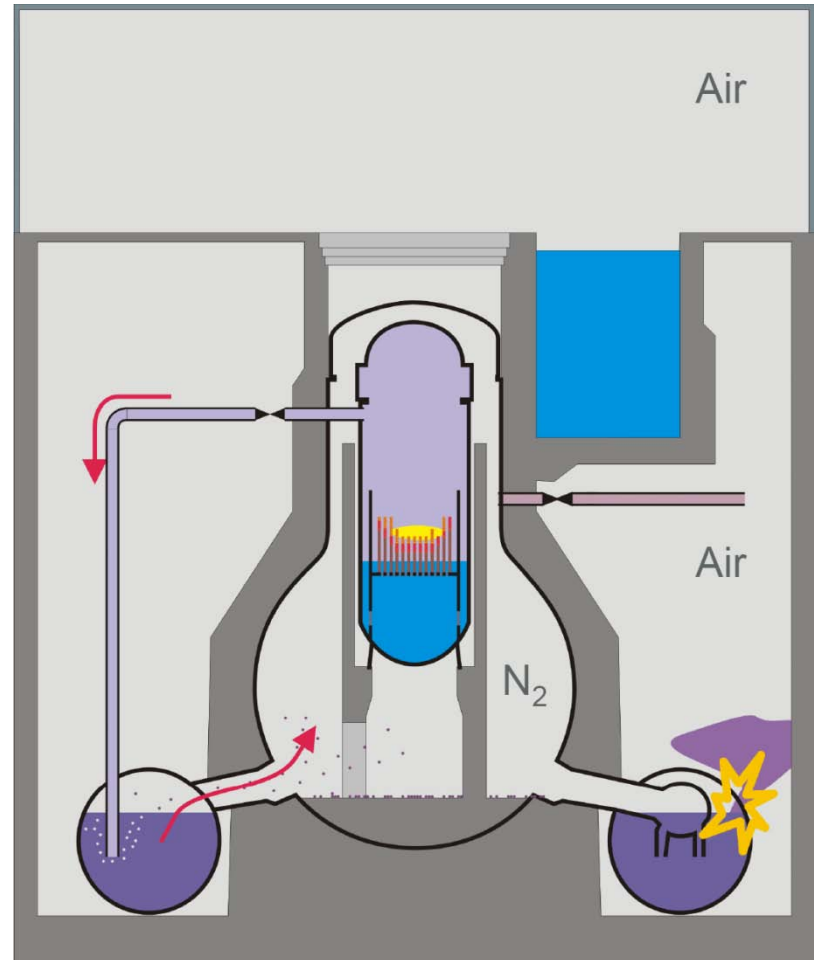
Damage to containment

Release of fission products

High radiation levels

Evacuation of the plant

Accident – level 6-7?



3-12. Chronology of Unit 3 after the earthquake (1/2)

● **Unit 3**

- 11th ● Under operation, Automatic shutdown by the earthquake
● Loss of A/C power
- 13th ● Loss of water injection function
● Started to vent
- 14th ● Unusual increase in PCV pressure
● Sound of explosion
- 16th ● White smoke generated
- 17th ● Water discharge by the helicopters of Self-Defense Force(4 times)
● Water spray from the ground by High pressure water-cannon trucks
(Police: once, Self-Defense Force: 5 times)
- 18th ● Water spray from the ground by same trucks (Self-Defense Force: 6 times)
Water spray from the ground by US water-cannon trucks
(US armed force:1 time)
- 19th ● Water spray from the ground by High pressure water-cannon trucks by
Hyper Rescue Unit of Tokyo Fire Department.

3-12. Chronology of Unit 3 after the earthquake (2/2)

● **Unit 3(Continued)**

- 20th ● Sprayed by Hyper Rescue Unit of Tokyo Fire Department
- 22nd ● Lighting in the Central Control Room was recovered.
- 23rd ● Injection of seawater to the SFP
- 24th ● Injection of seawater to the SFP
- 25th ● Water spray (Emergency fire support team)
● Started fresh water injection
- 27th ● Water spray by Concrete Pump Truck
- 28th ● Switched to the water injection to the core using a temporary motor-driven pump
● In order to prepare for transfer the stagnant water on the basement floor of turbine building to the Condenser, the water in the Condensate Storage Tank is being transferred to the Surge Tank of Suppression Pool Water
- 29th ● Started to spray freshwater by Concrete Pump Truck
- 31st ● White smoke was confirmed to generate continuously
● Fresh water is being injected to the spent fuel pool and the RPV

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3-16. Chronology of Unit 4 after the earthquake

● **Unit 4**

- 14th ● Water temperature in the Spent Fuel Pool, 84°C
- 15th ● Damage of wall in the 4th floor confirmed
● Fire occurred in the 3rd floor (12:25 extinguished)
- 16th ● Fire occurred. TEPCO couldn't confirm any fire on the ground.
- 20th ● Water spray over the spent fuel pool by Self Defense Force
- 21st ● Water spray over the spent fuel pool by Self Defense Force
- 22nd-24th ● Water spray (Concrete Pump Truck (3 times)
- 25th ● Injection of seawater to SFP via the Fuel Pool Cooling Line (FPC)
● Water spray (Concrete Pump Truck)
- 27th ● Water spray (Concrete Pump Truck)
- 29th ● Lighting in the Central Control Room was recovered.
- 30th ● White smoke was confirmed to generate continuously.
● Spray of fresh water (Around 140t) over the Spent Fuel Pool using Concrete Pump Truck (50t/h) was carried out.
● Fresh water is being injected to the spent fuel pool

31

3-17. Chronology of Unit 5 & 6 after the earthquake

● **Unit 5&6**

- 20th ● Unit 5 under cold shutdown (Water temperature of reactor water is less than 100°C)
● Unit 6 under cold shutdown (Water temperature of reactor water is less than 100°C)
- 21st ● Water spray over the Common Spent Fuel Pool started
- 22nd ● Recovering power supply of unit 5 and 6 is completed.
- 24th ● The power was started to be supplied. Cooling also started
- 30th ● Back up power of Unit 6 is in working condition and external power was supplied to Unit 5 as of March 30th

Spent fuel pools

15-16.3.2011

Spent fuel pools outside reactor containment

No external cooling
Leakage of pools?

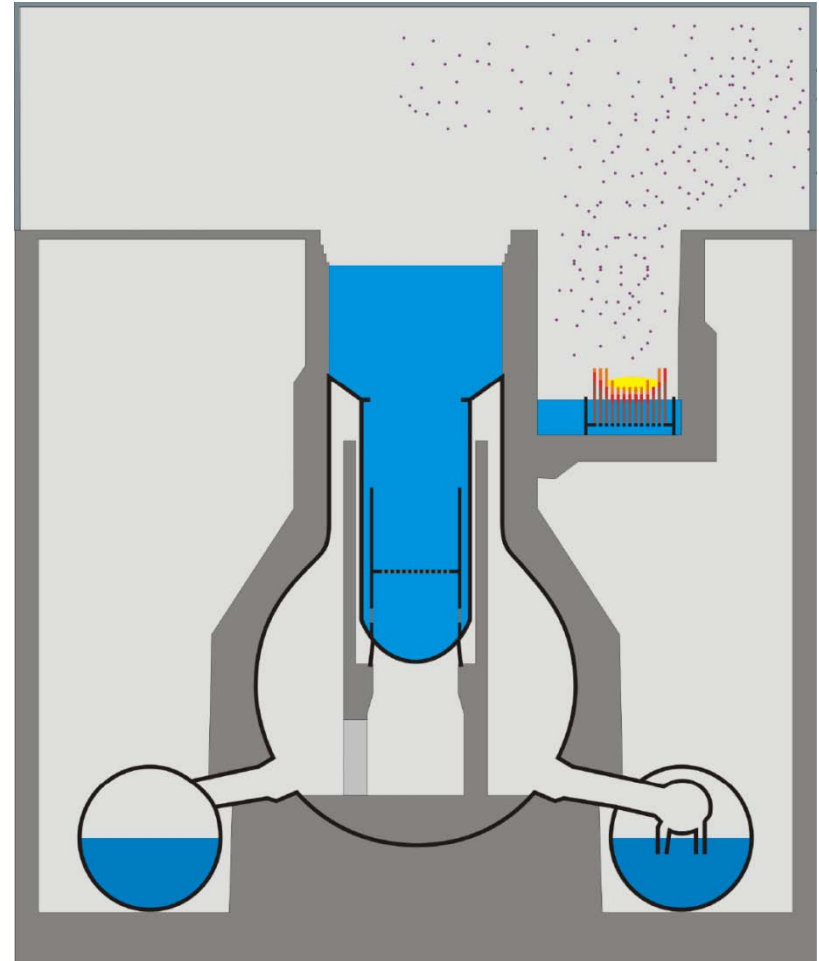
Passive cooling:

Unit 4 ~ days

Units 1-3,5,6 ~ weeks

Meltdown of spent fuel?
Large releases?

Accident – level 7?

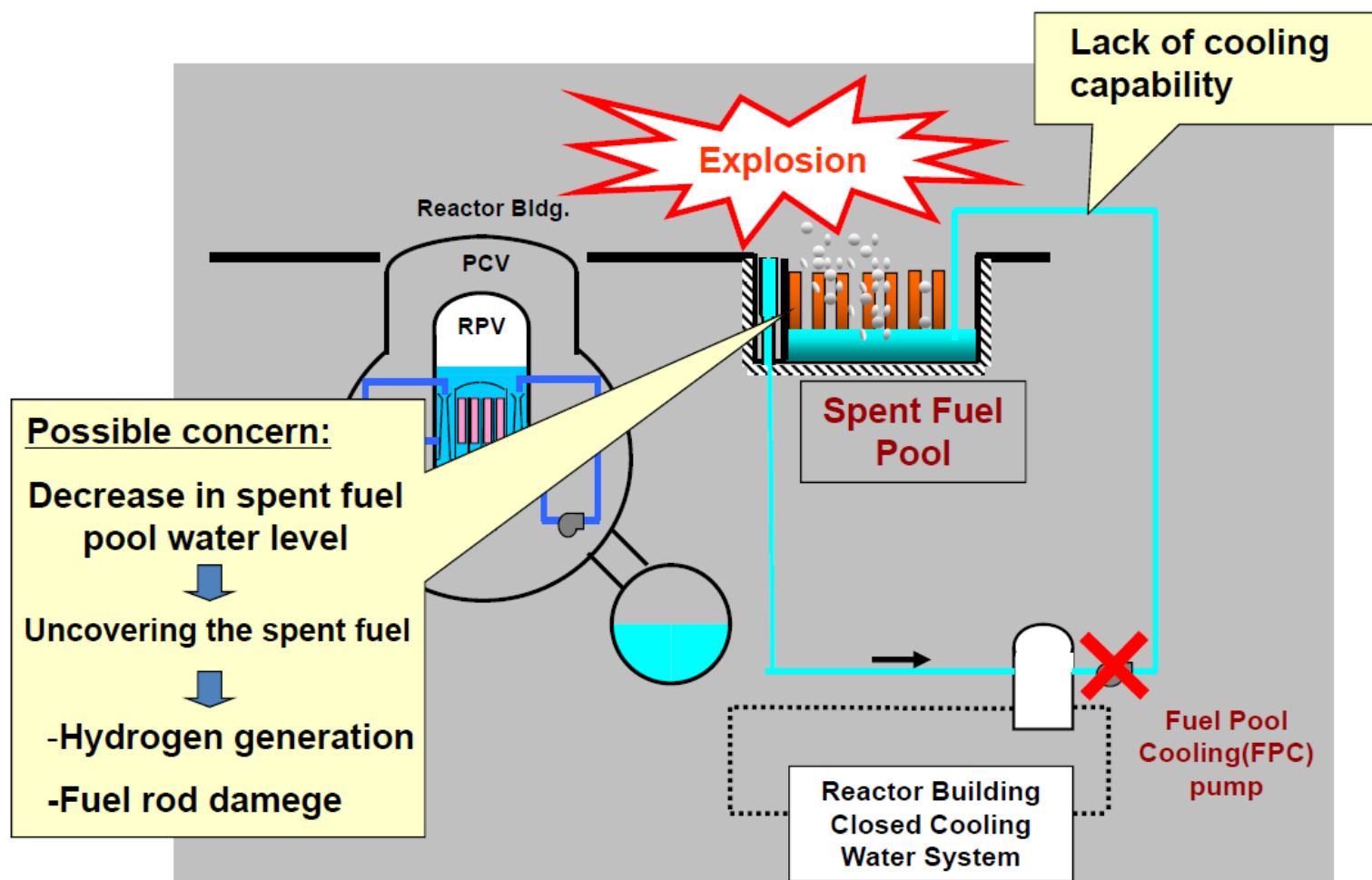


Report concerning incidents at spent fuel pools in the Fukushima Dai-ichi NPS



Photo: Water spray into the SFP in Unit 4 using concrete pump truck

4-1. Possible concerns about Spent Fuel Pool

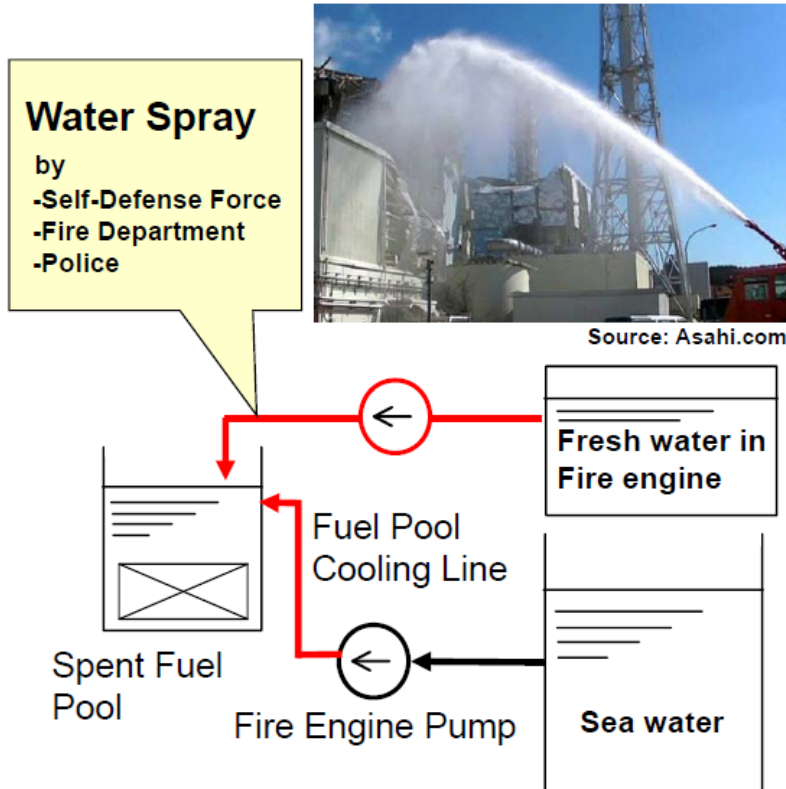


34

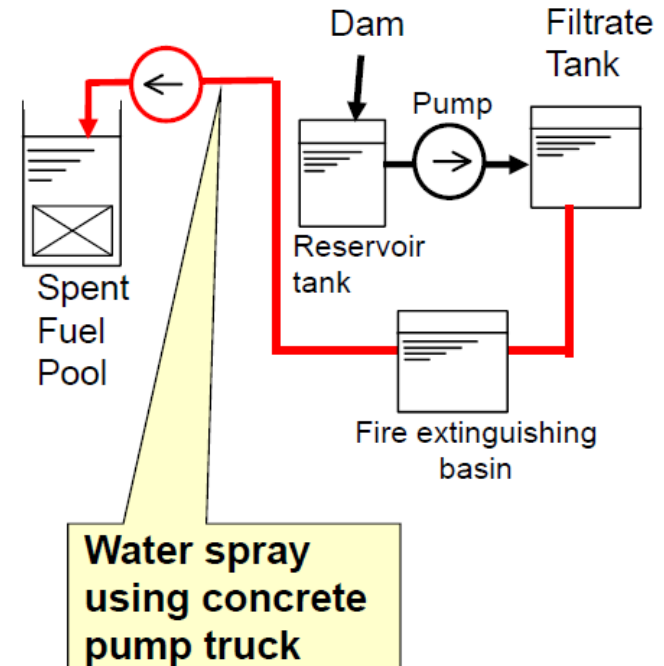
4-3. Measures taken to cool the Spent Fuel Pool (2/4)

Unit 3

【1st Stage】 Sea water injection



【2nd Stage】 Fresh water injection



* Sea water discharge by helicopters
of the Self Defense Force

37

Current status – 27.4.2011

**Partial meltdown of fuel in
reactors 1-3**

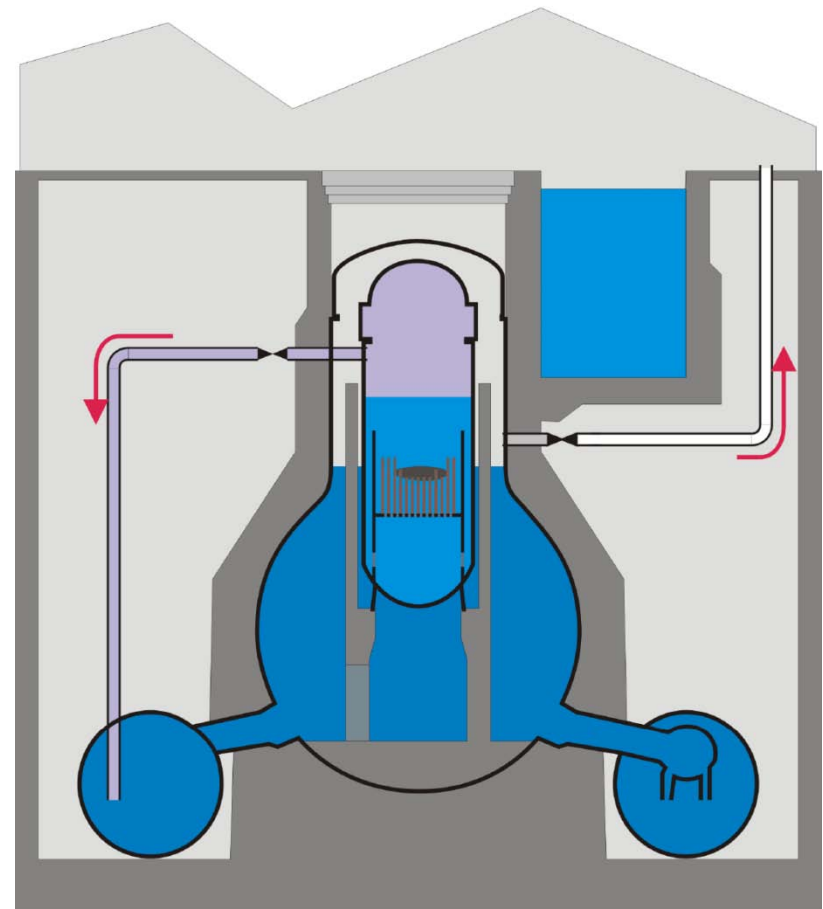
**Damage to containment in unit
2**

(~~Damage to spent fuel in unit 4~~)

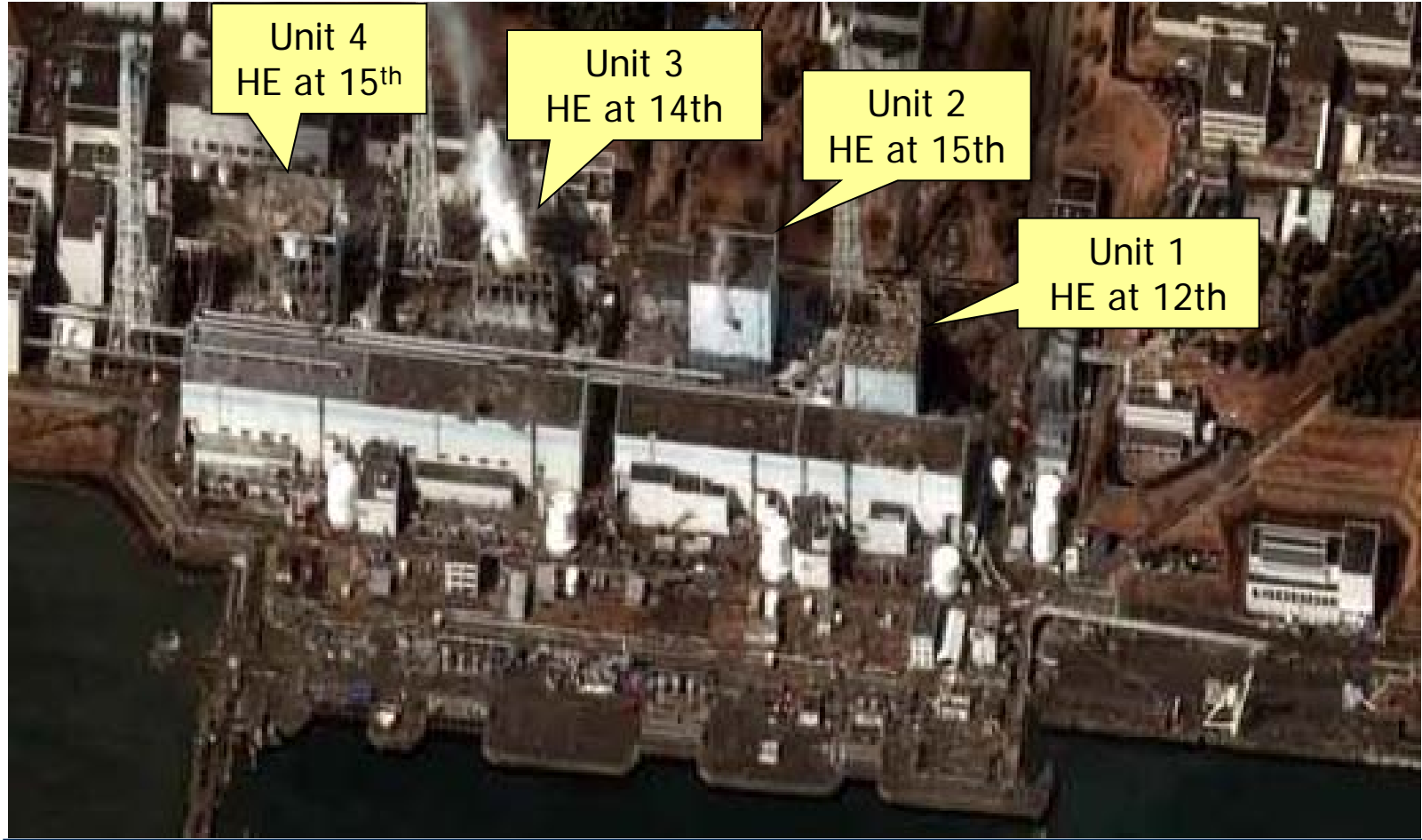
Feed of water in reactor pressure
vessels, pools

External power to units 1-4 but no
external cooling

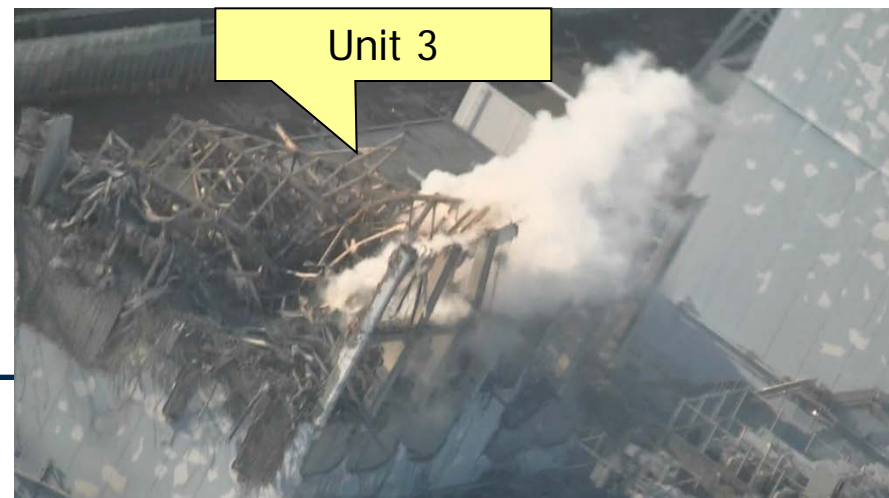
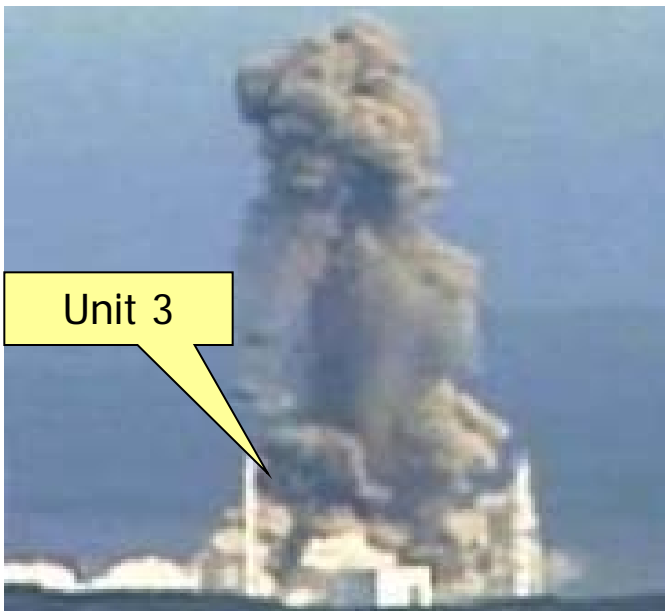
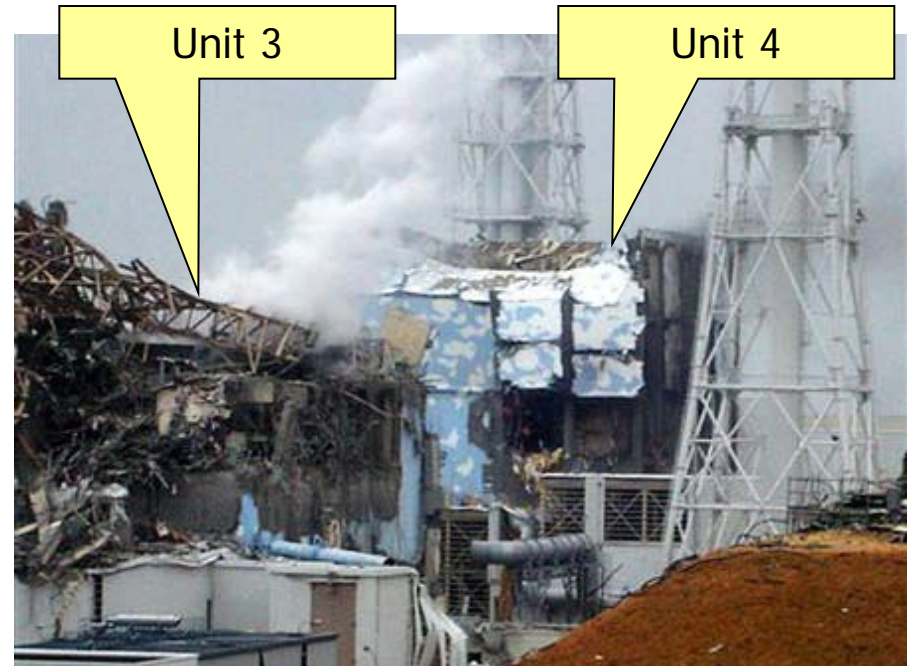
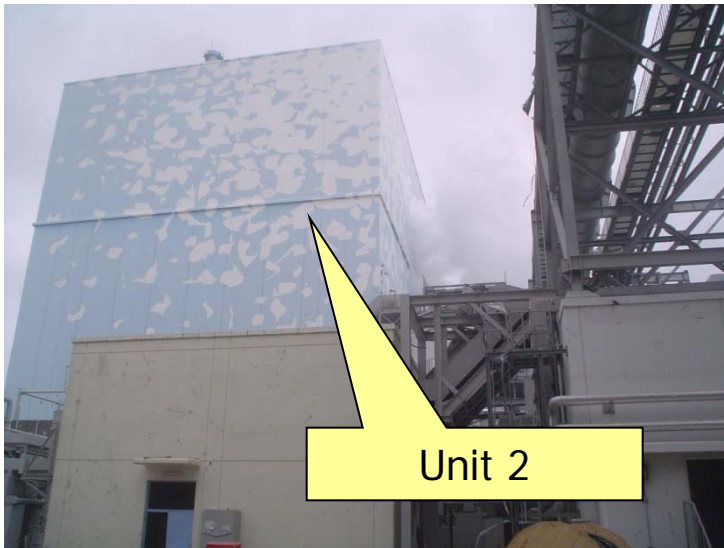
Accident – level 7?



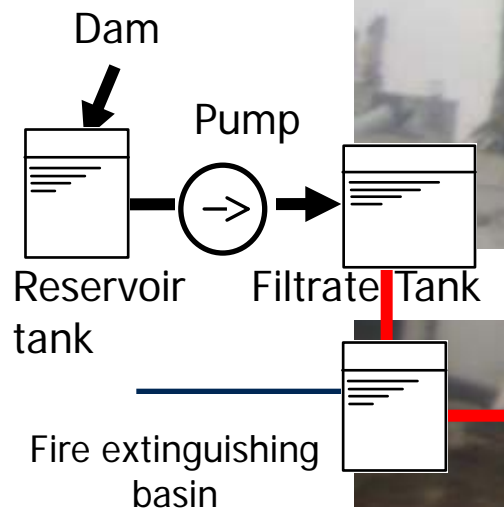
View of Units 1, 2, 3, 4 After Explosions



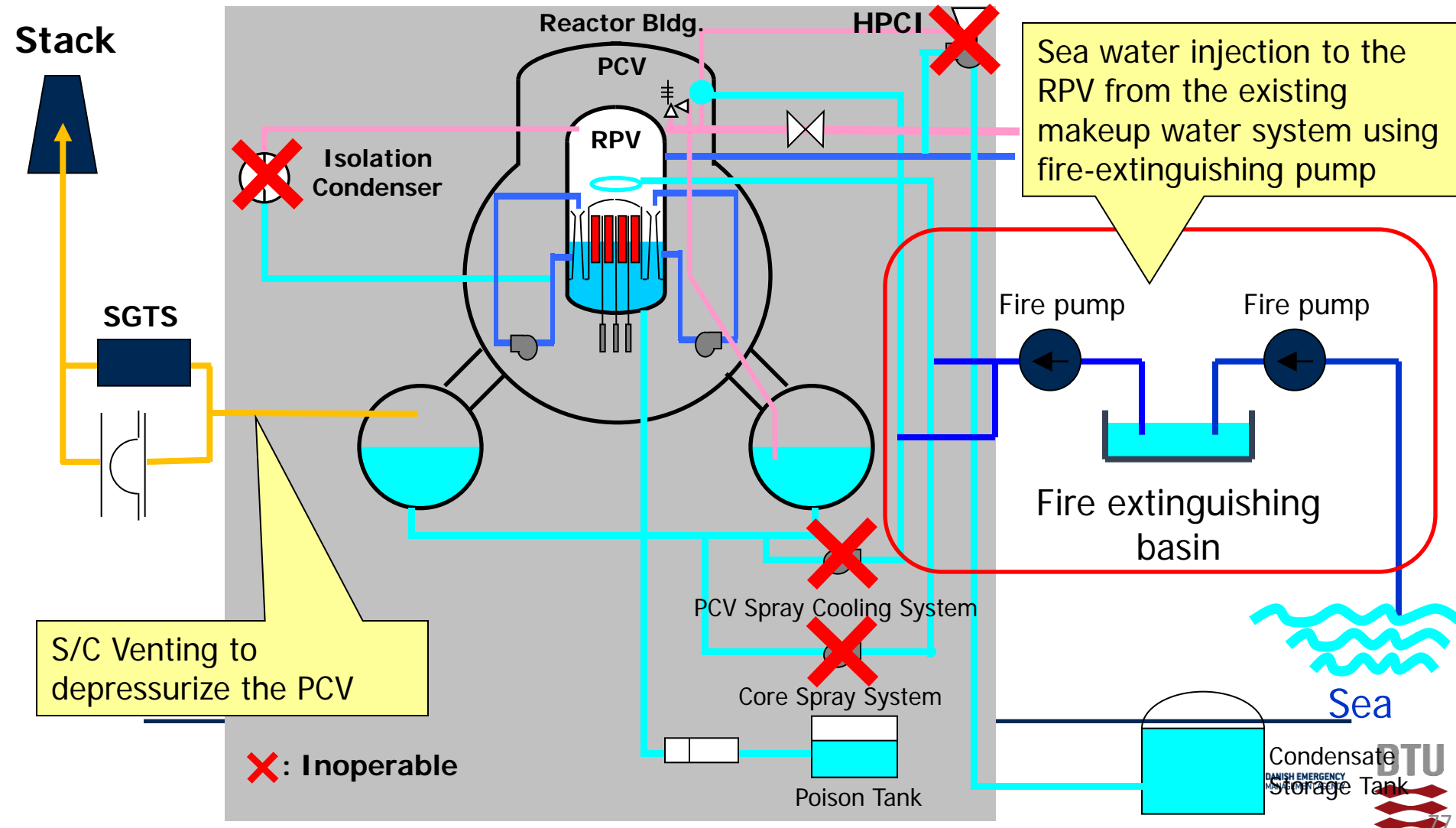
Accident Progression at Units 2, 3, 4



Water spray into the SFP of Unit 4 using concrete pump truck



- Sea water injection using fire water pump - S/C
Venting to depressurize the PCV*



INES

- INES 3 (“Defense in Depth”)
- INES 4 (12 March) “Radiological Barriers and Control”
- INES 5 (18 March)
- INES 7 (Release)

APPENDIKS A: INES, den internationale skala for uheld på nukleare anlæg

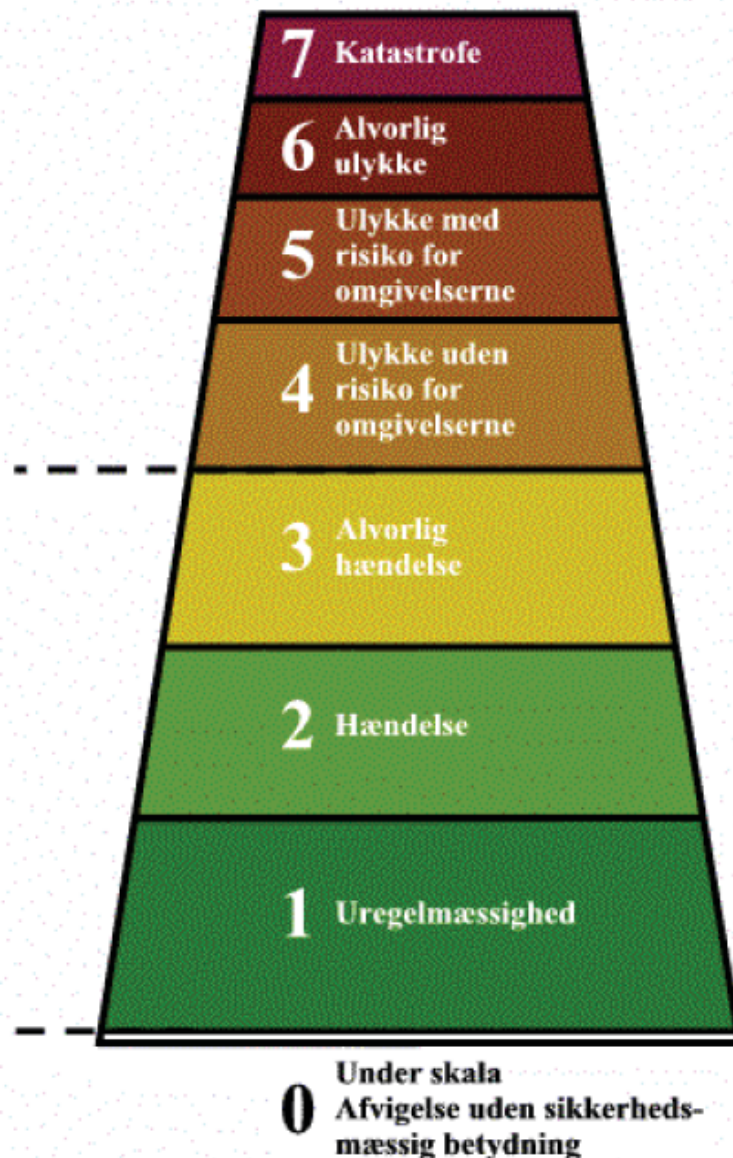
På foranledning af IAEA og OECD/NEA blev der i 1990 udviklet en skala til angivelse af den sikkerhedsmæssige betydning af uheld på nukleare anlæg og uheld ved transport af radioaktivt materiale.

Skalaen betegnes INES, International Nuclear Event Scale, og omfatter otte uheldsklasser, fra klasse 0 til 7 (se figuren). Hændelser, der ikke har nogen sikkerhedsmæssig betydning, placeres i klasse 0, mens alvorlige ulykker med udslip af store mængder radioaktivt materiale hører til klasse 7.

Uheldsklassen bestemmes ud fra tre kriterier:

- Påvirkning af omgivelserne
- Påvirkning af anlægget
- Degradering af dybdeforsvaret (anlæggets sikkerhedssystem).

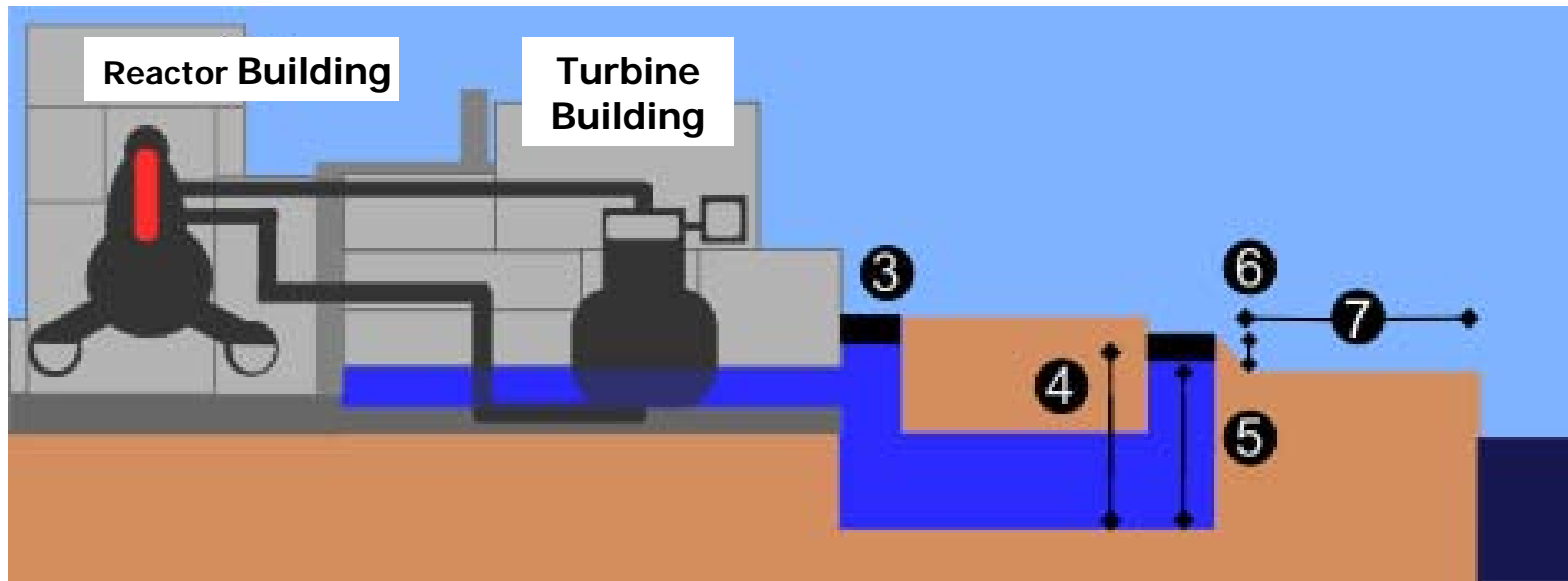
Uheld med påvirkning af omgivelserne ved udslip af radioaktivt materiale er det mest alvorlige kriterium og dækker klasse 3 til 7. Uheld, hvor der udelukkende sker en



Water leakage in trenches

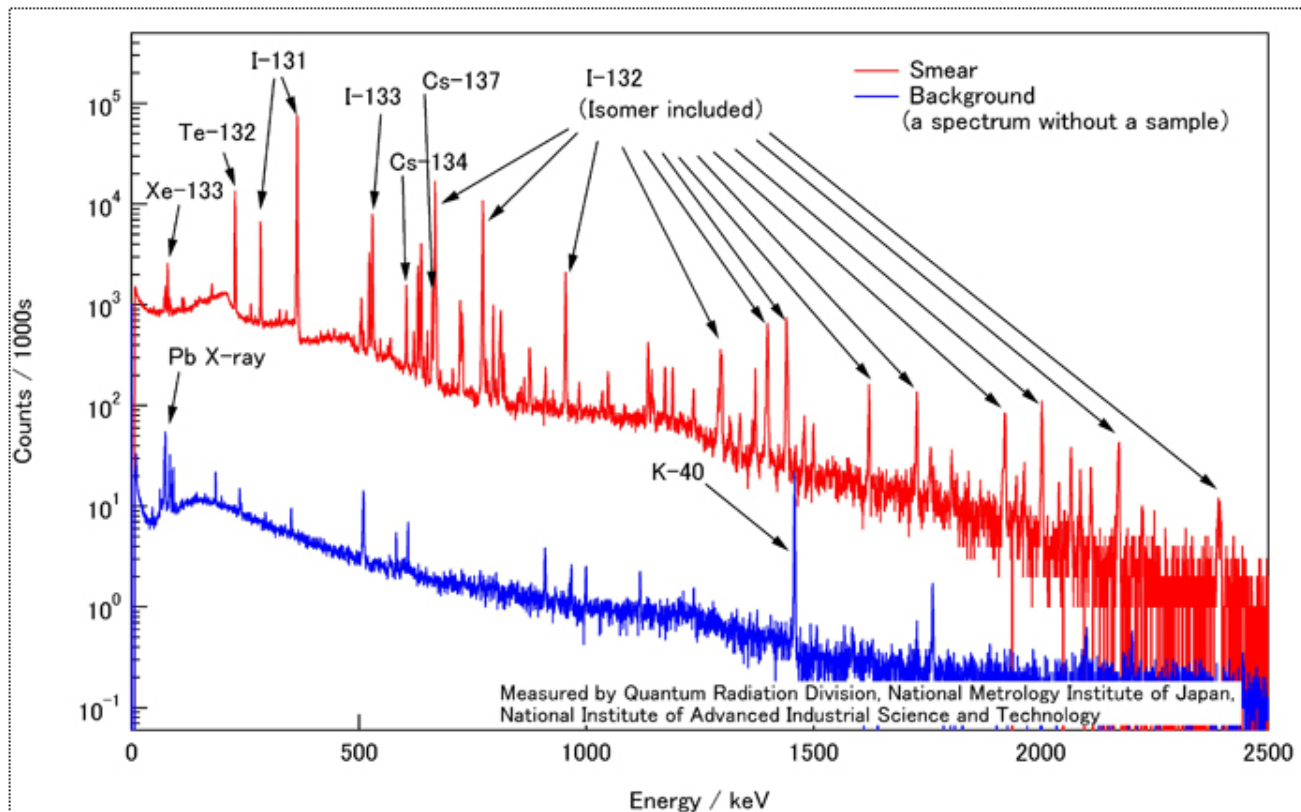
- Highly radioactive water was found in trenches at Units 1, 2 and 3

The Units 2 and 3 trenches were 1 m below the level at which they would overflow into the sea. On the other hand, the unit 1 trench was 10 cm from overflowing. (As of March. 30th)



Side view of the Fukushima trenches and tunnels (*Source: Wikipedia*)

Målte isotoper i nedfaldet



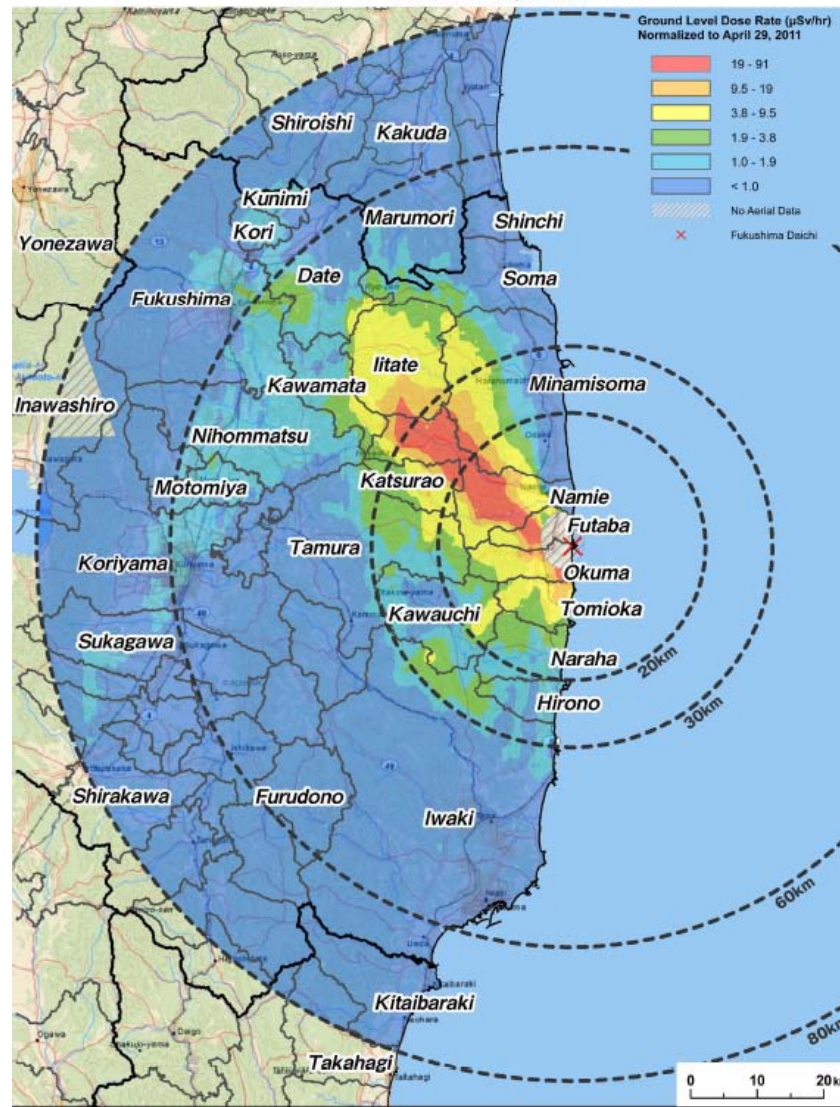
Photon energy spectra from the fallout sample smeared on the vinyl sheet on the ground (red) at 9:30 March 15, 2011, and the background (blue).

Evacuation, Sheltering, Stable Iodine

- March 11, 21:23 hrs: Government directed **evacuation** of residents **within 3 km radius** of Fukushima Dai-ichi
- March 12, 05:44 hrs: Government directed **evacuation** of residents **within 10 km radius** of Fukushima Dai-ichi
- March 12, 18:25 hrs: Government directed **evacuation** of residents **within 20 km radius** from Fukushima Dai-ichi
- March 15: Local Emergency Response Headquarter issued direction to **administer stable Iodine** during evacuation from the 20 km radius evacuation area
- **Sheltering** of residents was implemented in the area from 20km to 30km of Fukushima Dai-ichi; and, cooperating with Fukushima Prefecture, livelihood support to the residents in the sheltering area are implemented.
- March 25: Chief Cabinet Secretary announced **voluntary evacuation** of residents within the area from 20 km to 30 km of Fukushima Dai-ichi

Aerial Measuring Results

Joint US / Japan Survey Data



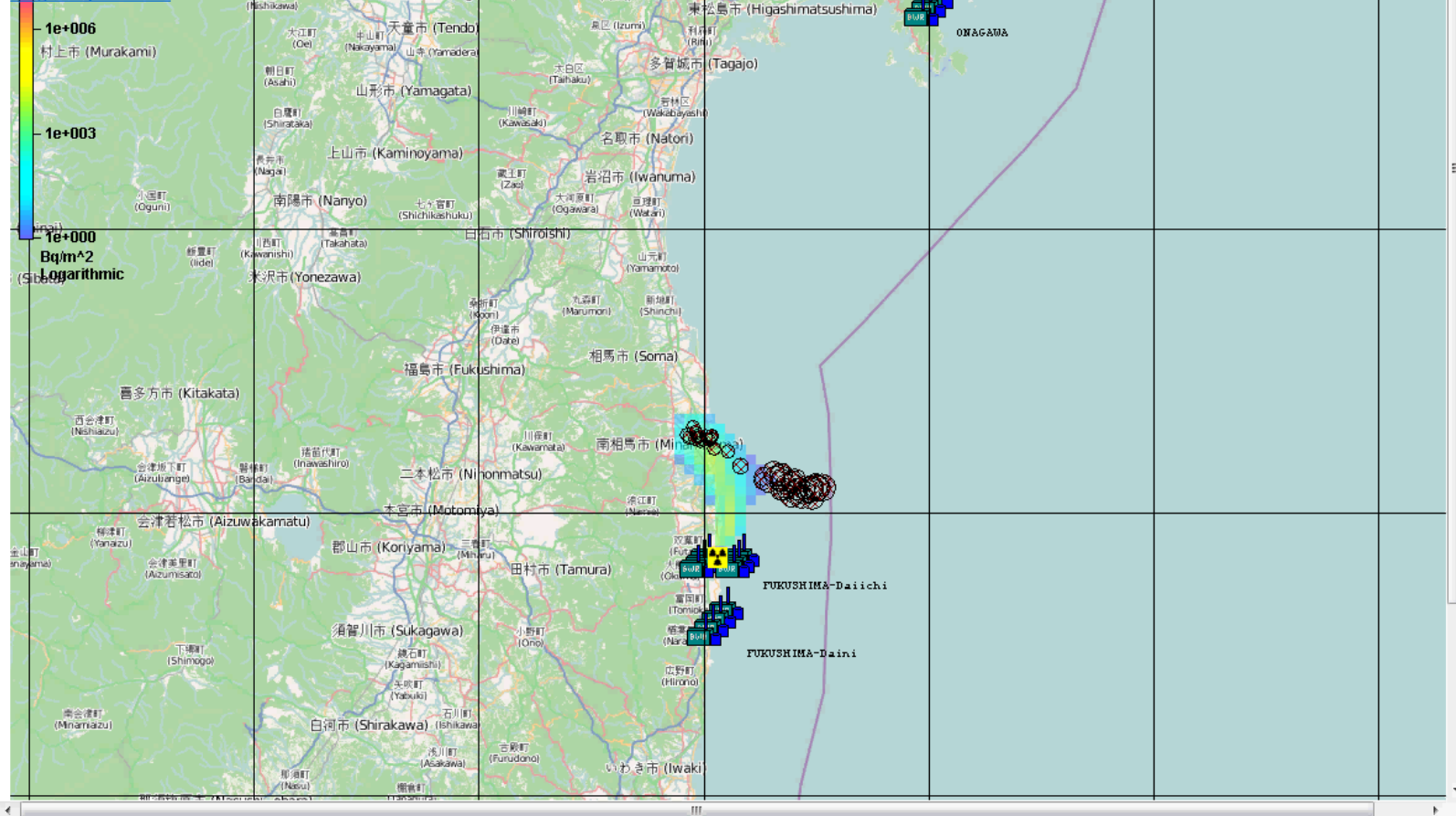
Reactor Details

Deposition on Ground

Situation: GMT 09:30:00 03/12/11 for nuclide Cs-137

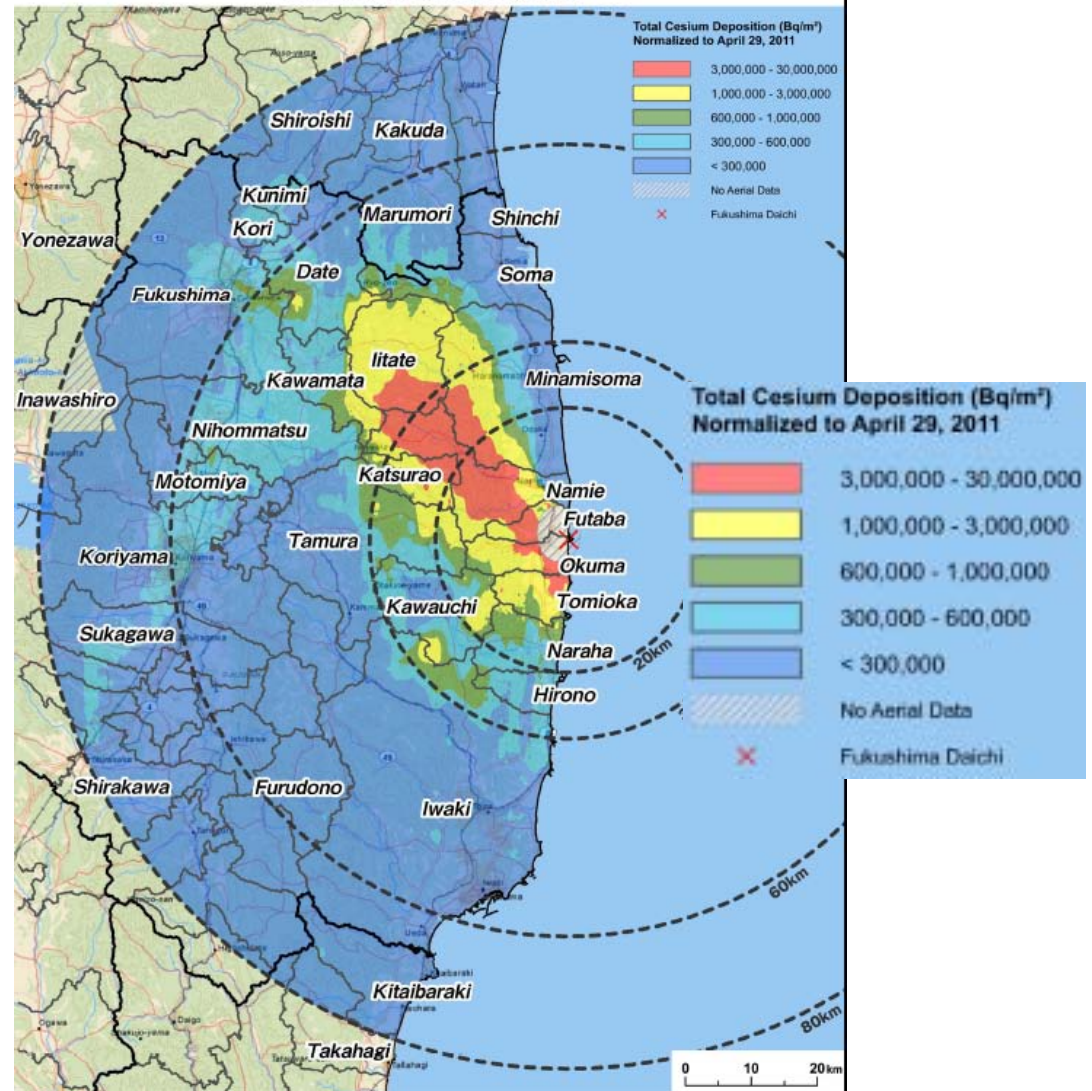
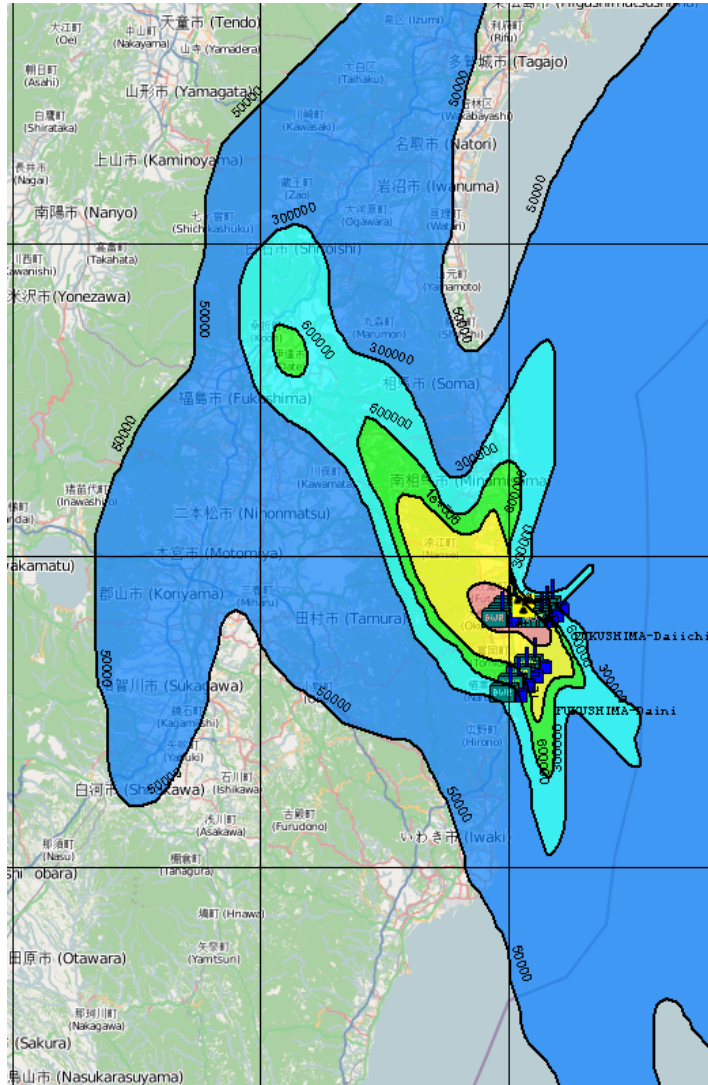
Prognosis ran from GMT 06:30:00 03/12/11 to GMT 04:04:00 03/17/11

Prognosis parameters



Aerial Measuring Results

Joint US / Japan Survey Data

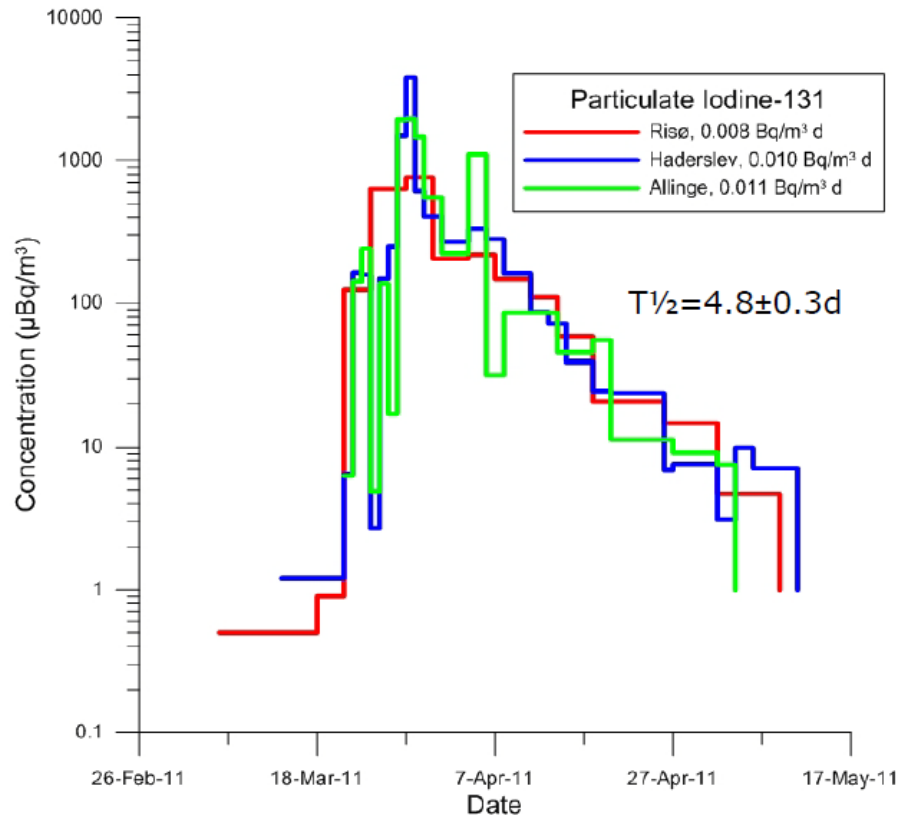


Risø/BRS målestationer

Iodine-131 in Air in Denmark



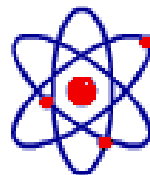
- Samples based on collection of particles in air by filtration
- Thus gaseous fraction of iodine not collected
- Other labs in Europe using filters and charcoal cartridges for air sampling found two to ten times more gaseous than particulate iodine
- Time-integrated concentrations of ^{131}I in air at three Danish locations range from 0.008 to 0.011 $\text{Bq/m}^3 \text{ d}$.



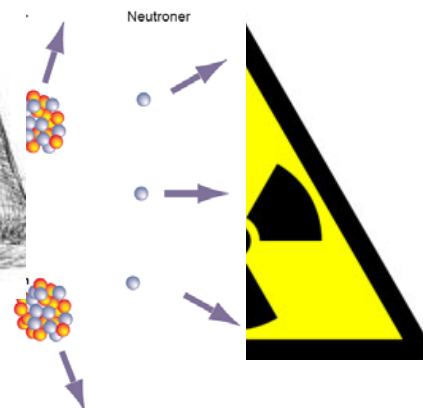
En ny Tjernobyl ulykke?

Fire krav til sikkerhed

1. Stabil drift



2. Sikker nedlukning



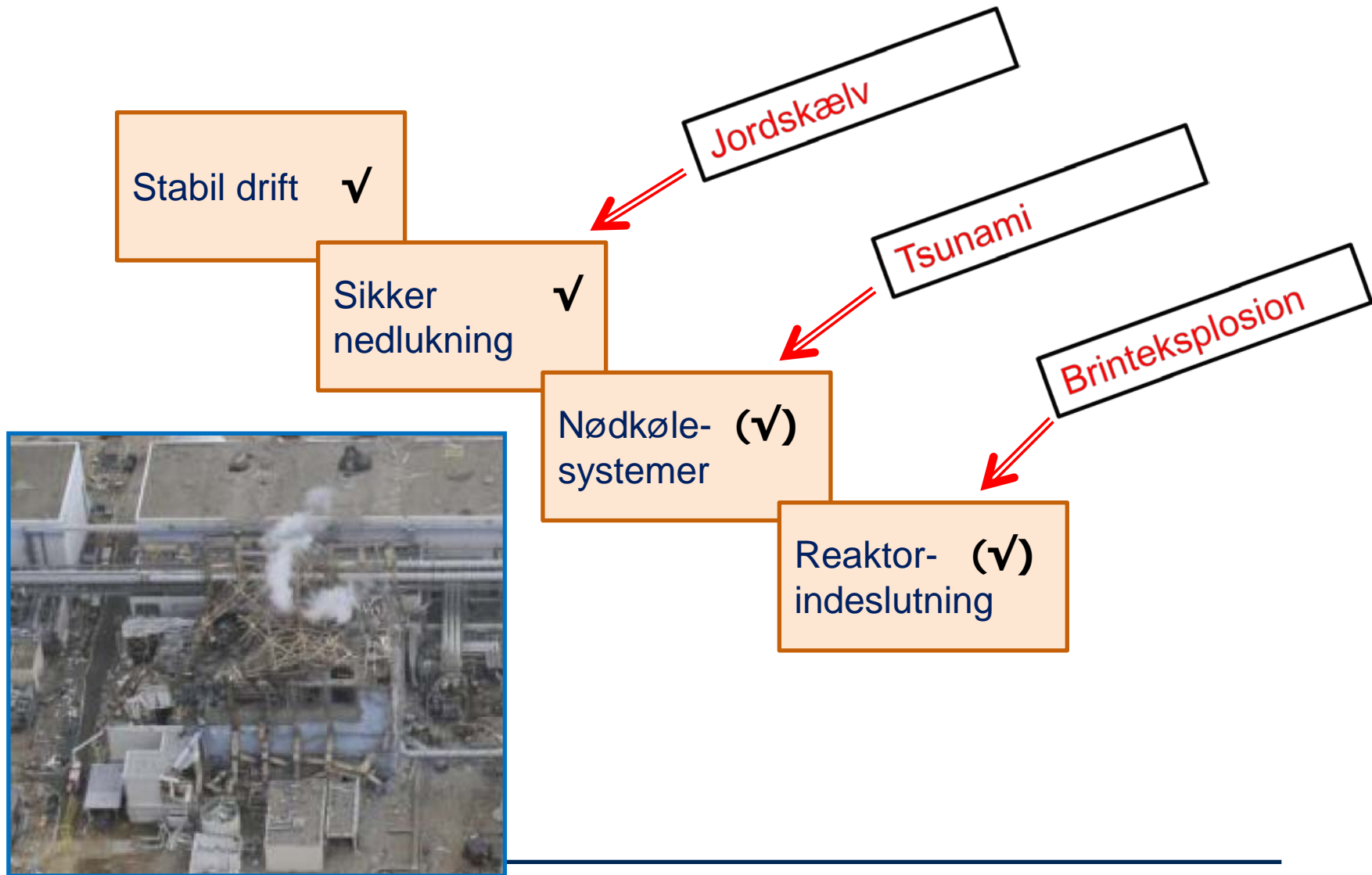
Figur 3a Fissionsprocessen

3. Nødkøle-systemer

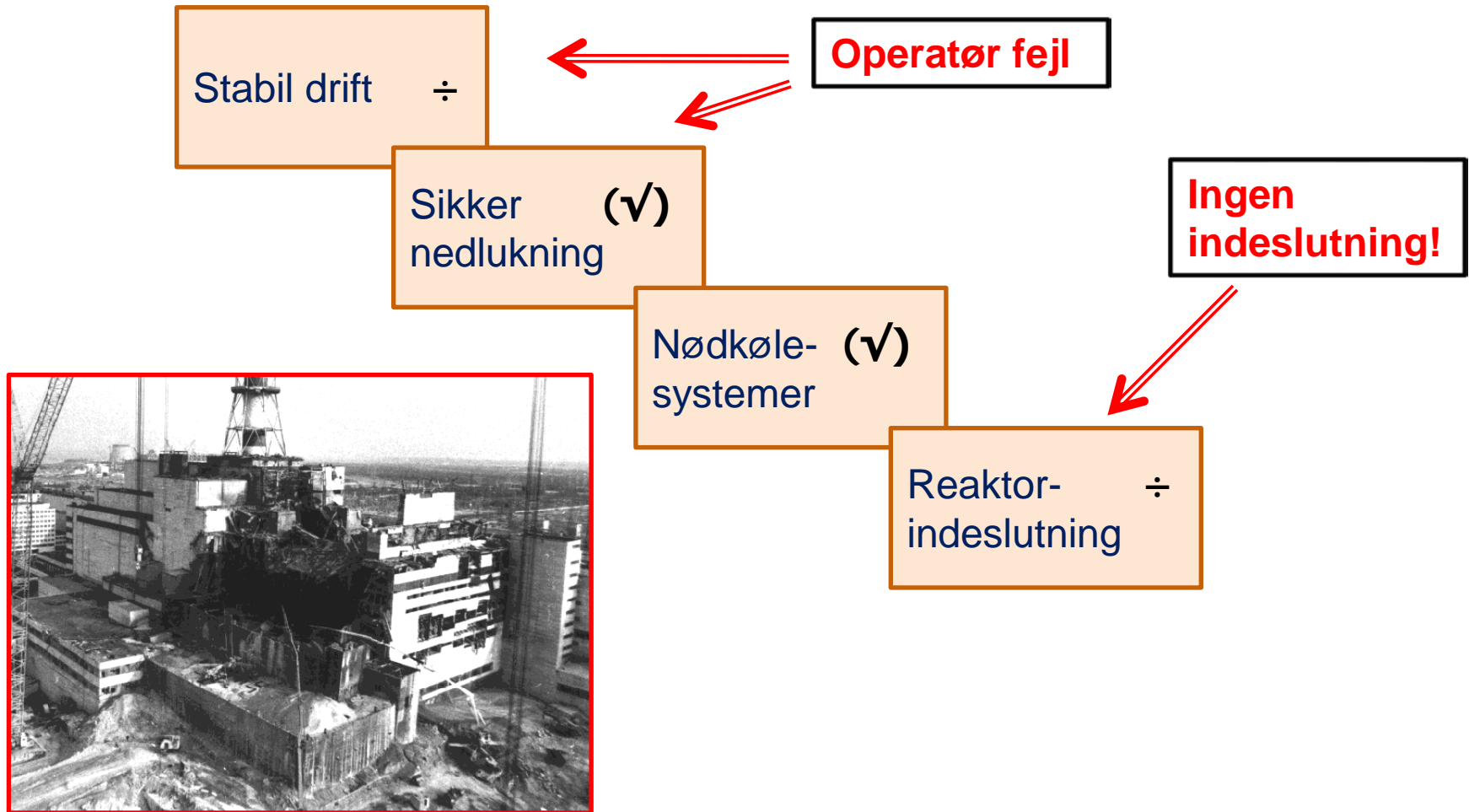
4. Indeslutning



Reaktorsikkerhed: Fukushima



Reaktorsikkerhed: Tjernobyl



Source Term

	Assumed amount of the discharge from Fukushima Dai-ichi (1F)		(Reference) Amount of the discharged from the Chernobyl accident
	NISA's estimation ^{*1}	NSC's estimation ^{*2}	
$^{131}\text{I} \dots (\text{a})$	$1.3 \cdot 10^{17} \text{Bq}$	$1.5 \cdot 10^{17} \text{Bq}$	$1.8 \cdot 10^{18} \text{Bq}$
^{137}Cs	$6.1 \cdot 10^{15} \text{Bq}$	$1.2 \cdot 10^{16} \text{Bq}$	$8.5 \cdot 10^{16} \text{Bq}$
(Converted value to ^{131}I) ^{*3} ... (b)	$2.4 \cdot 10^{17} \text{Bq}$	$4.8 \cdot 10^{17} \text{Bq}$	$3.4 \cdot 10^{18} \text{Bq}$
(a)+(b)	$3.7 \cdot 10^{17} \text{Bq}$	$6.3 \cdot 10^{17} \text{Bq}$	$5.2 \cdot 10^{18} \text{Bq}$

(notes)

*1: Estimation by NISA is based on the numerical analysis of accident transient

*2: NSC calculated backward of monitoring data to estimate the amount of discharge

*3: multiplication factor of radiological equivalence to ^{131}I is 40

Foreløbige konklusioner

- Fukushima ulykken er den **næstmest alvorlige ulykke** på et kernekraftværk
- Ingen **umiddelbare skader** på mennesker. Antal cancertilfælde vil være **begrænset**, da de mest udsatte befolkningsgrupper blev evakueret
- Det vil tage **6-9 måneder**, at få reaktorerne under kontrol (kold nedlukning)
- Reaktorerne 1 - 3 er **ødelagte**. Det vil tage adskillige år og kræve robotudstyr at nedbryde reaktorerne
- Vi kender kun delvist omfanget af den **lokale forurening**

Forhøjet baggrundsstråling



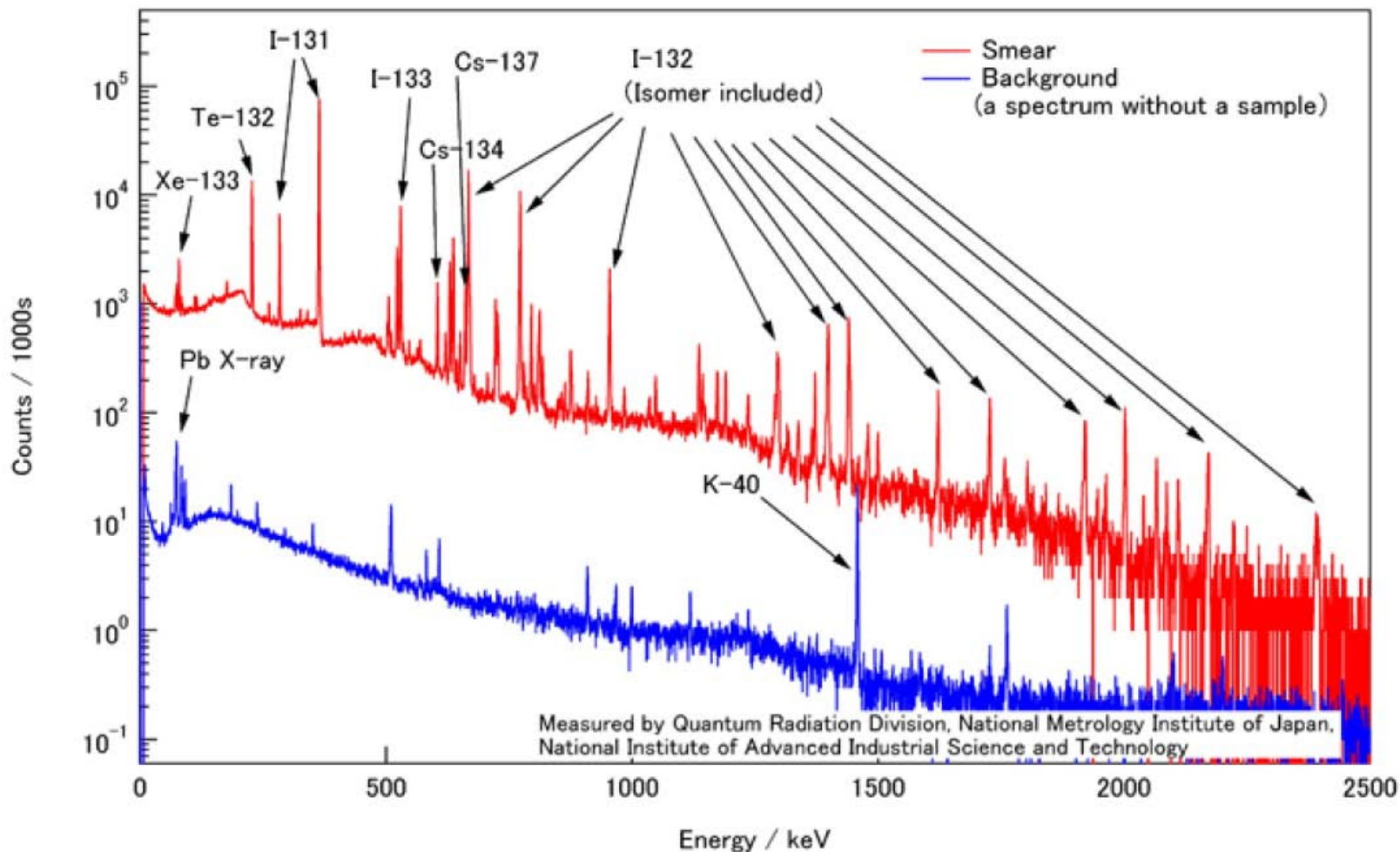
μSv/hour
(April 10)

Fukushima Dai-ichi NPP

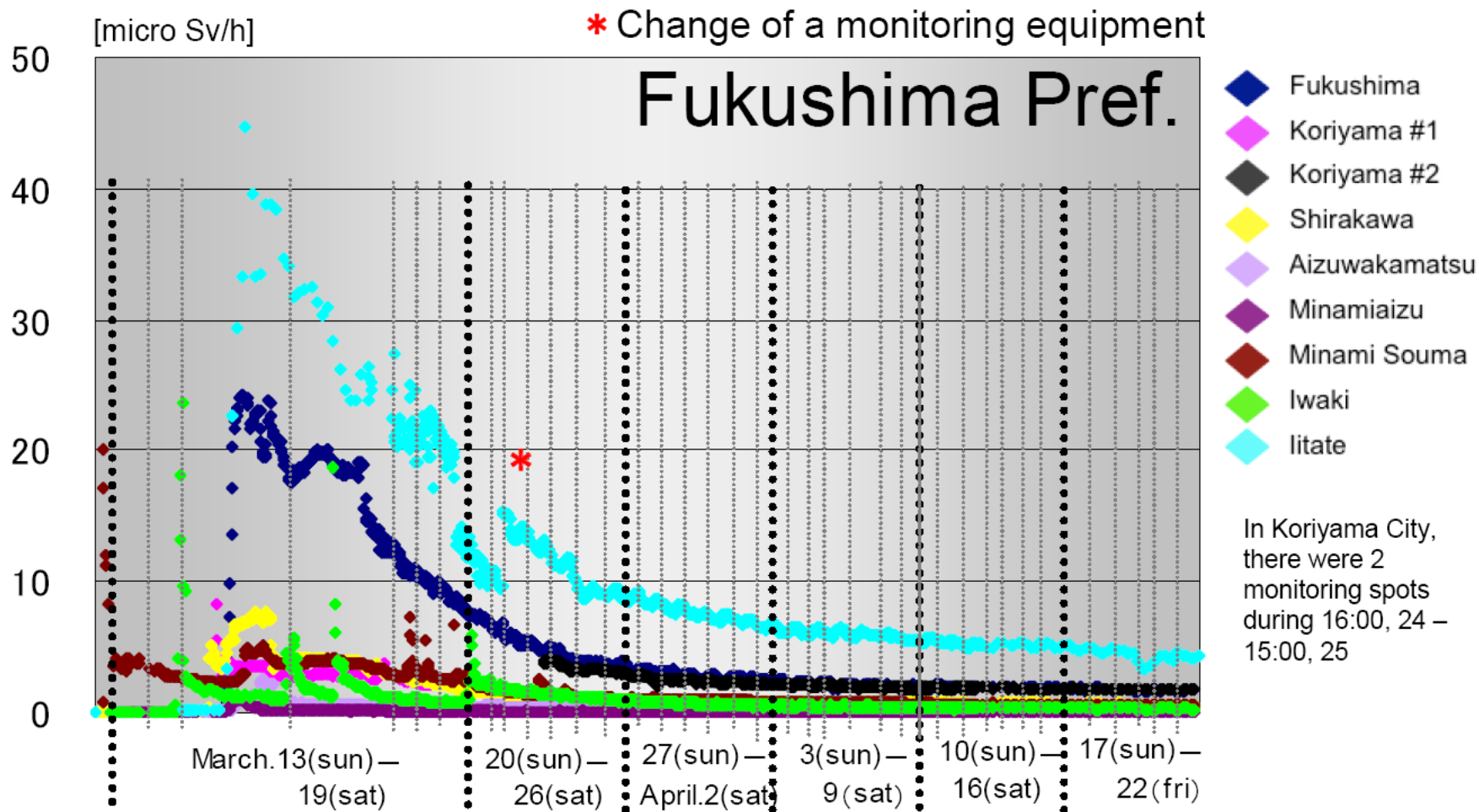
Fukushima Dai-ni NPP

Radioaktivt nedfald fra Fukushima

15.3.2011



Baggrundsstråling i Fukushima Præfektoret

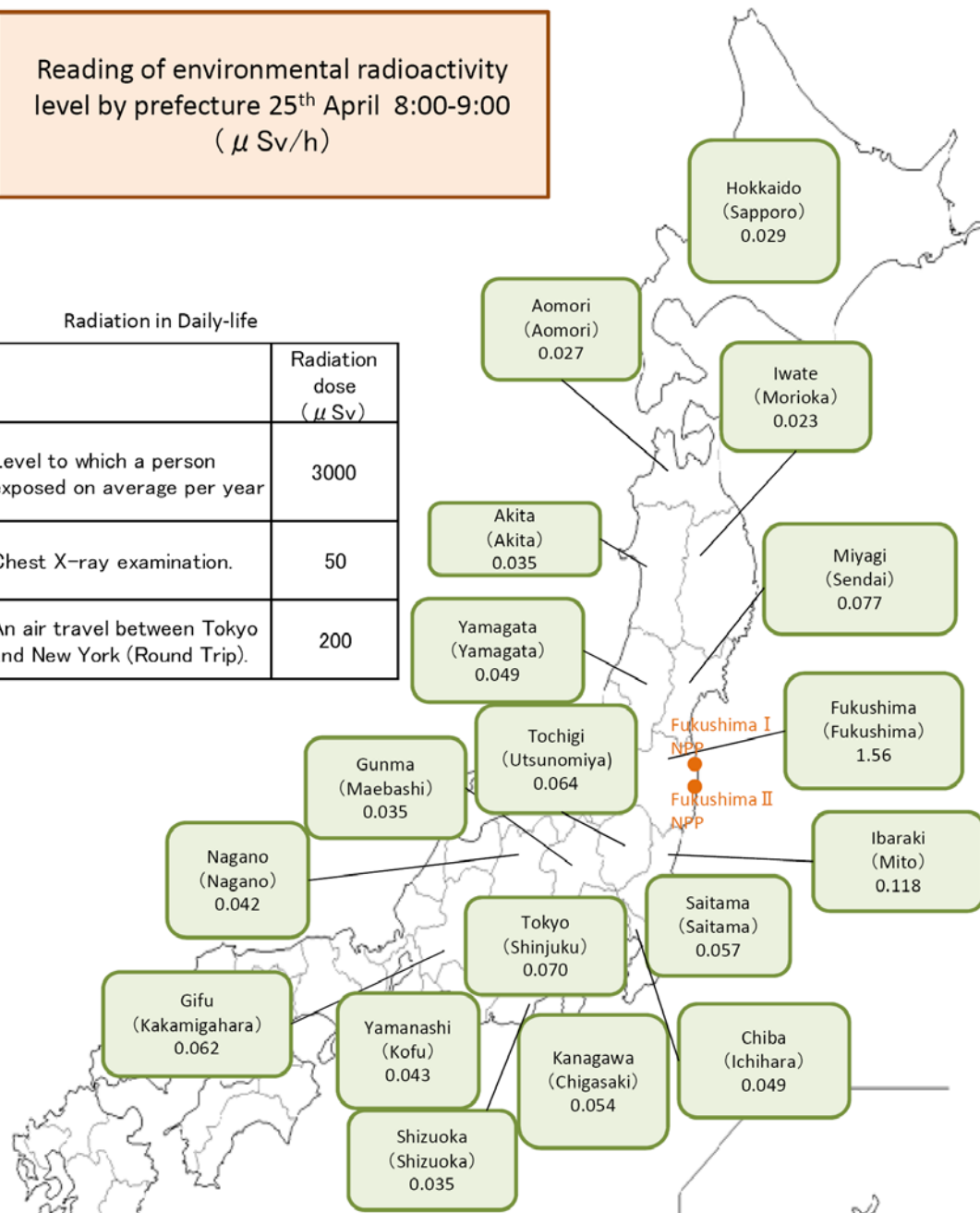


Måling 25. april

Reading of environmental radioactivity
level by prefecture 25th April 8:00-9:00
($\mu\text{Sv/h}$)

Radiation in Daily-life

	Radiation dose (μSv)
Level to which a person exposed on average per year	3000
Chest X-ray examination.	50
An air travel between Tokyo and New York (Round Trip).	200



Outline

- Kernekraft – hvorfor og hvordan
- Fukushima ulykkens hændelsesforløb
- Status pr. 7. september 2011
- Kernekraft efter Fukushima

Status pr. 7. september 2011

Plant Status: Fukushima Daiichi

- Units 1-3: Implementing circulating water cooling reusing the accumulated water in order to cool the fuels in reactors.
- Units 1-4: Have launched stable circulating cooling in order to cool the fuels in spent fuel pool (SFP).
- Units 1-3: Found contaminated water with high radioactive materials in turbine buildings. Continuation on decontamination of the water by processing facility.
- Units 1-3: Injecting N₂ into PCV to lower the possibility of hydrogen explosion.
- Units 5&6: Under cold shutdown.

		#1 460MW	#2 784MW	#3 784MW	#4 784MW	#5 784MW	#6 1,100MW
Shutdown		○ Automatic Shutdown			Shutdown for Outage		
Cooling	Reactor	△ Circulating Water Cooling Injecting N ₂	△ Circulating Water Cooling Injecting N ₂	△ Circulating Water Cooling Injecting N ₂	— Fuels have been removed	○ Cold Shutdown	○ Cold Shutdown
	Pool	○ Circulating cooling system	○ Circulating cooling system	○ Circulating cooling system	○ Circulating cooling system	○	○
*Containment		△ Highly contaminated water has been found Began decontamination of the water by processing facility	△ Highly contaminated water has been found Began decontamination of the water by processing facility	△ Highly contaminated water has been found Began decontamination of the water by processing facility	△	○	○

Plant Parameters (Fukushima Daiichi) as of September 7 at 12:00

RPV Pressure [MPa-g]

Unit 1	Unit 2	Unit 3
0.017	0.015	-0.100

RPV Temp [°C]

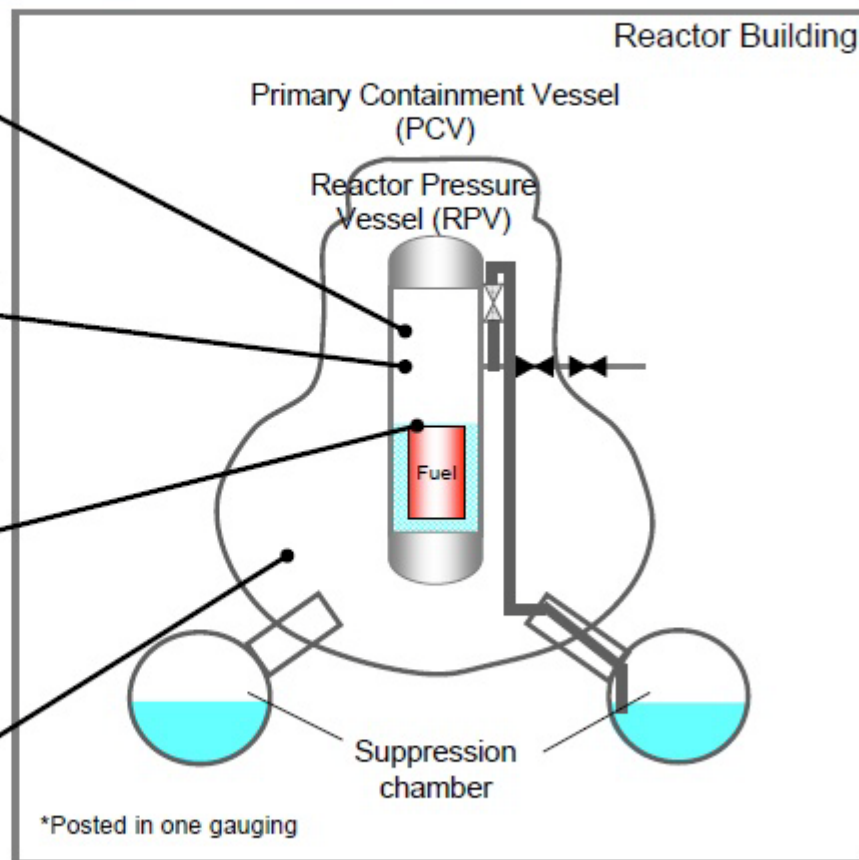
Unit 1	Unit 2	Unit 3
91.2 (Feedwater Nozzle)	113.0 (bottom of RPV)	103.0 (Feedwater Nozzle)

Reactor water level [mm]

Unit 1	Unit 2	Unit 3
Below the range	-2,200	-3,050

Drywell pressure [MPa-abs]

Unit 1	Unit 2	Unit 3
0.1247	0.116	0.1015



*We are judging the plant status by utilizing data obtained from multiple instruments including their changing trend in a comprehensive manner considering that some of them possibly are showing inaccurate data due to the irregular condition for use

Pressure conversion: Gauge pressure (MPa-g)=absolute pressure (MPa-abs)-atmospheric pressure(0.1013Mpa)

Situationen for kernekraft efter Fukushima ?

- Tyskland indstiller driften af 7 enheder og går tilbage til den oprindelige beslutning om en total udfasning i 2022 af de resterende 12 enheder
- Schweiz stopper for udbygning
- Belgien stopper for udbygning
- Kina standser for en tid udbygningen
- Japan indstiller driften af de fleste af deres 54 enheder for nærmere undersøgelse af jordskælv/tsunami sikringen (1/8-2011 var 18 enheder i drift)

Situationen for kernekraft efter Fukushima ?

- Stress test af nukleare værker i Europa
 - Modstandsevne over for oversvømmelser og jordskælv
 - Tilstrækkeligheden af værkernes nødstrømsforsyninger
 - Tilstrækkeligheden af værkernes vandforsyninger
 - Tilstrækkeligheden af kølesystemet for brændselsbassinerne
 - Recombiner egenskaberne

Stress testen skal være gennemført med tilfredsstillende resultat inden udgangen af 2011

Situationen for kernekraften på længere sigt

- Erstatte Zr-cladding med en legering, som ikke udvikler store mængder brint ved iltning
- Nyt og forbedret design af nødstrømsforsyninger
- Større vandreservoirer
- Mere passive designelementer, som ikke kræver strøm
- Bedre separation af enhederne på de enkelte sites
- Re-design af brændselsbassiner
- Bedre uddannelse af operatørerne i accident progressing (er procedurerne tilstrækkelige?)